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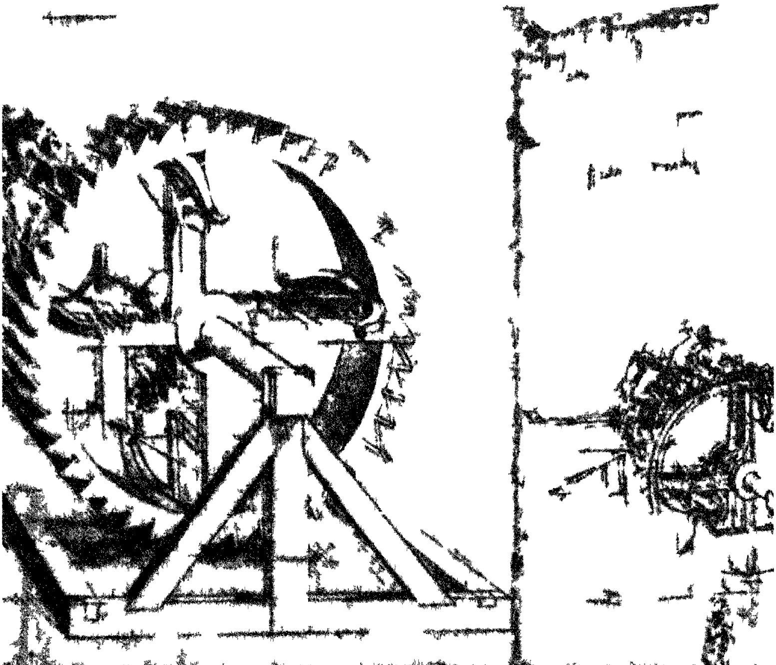

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Toward Modern Science

Volume I

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PREFACE

The interest and importance of the history of science today far transcend a mere intellectual curiosity about earlier stages of modern science. For the scientist working at the frontiers of knowledge, the history of his special discipline may be of definite heuristic value, furnishing a series of exemplary earlier problems together with the steps (including rejected hypotheses) that led eventually to their solution. For the non-scientist, concerned to orient himself in fields of knowledge which become daily more technical and esoteric, the study of the history of science holds out a hope—perhaps the last hope—for understanding what, in general, today's scientists are doing. For anyone interested in cultural history—not least in how we have arrived at our present cultural dilemmas—the history of science offers an unsurpassed body of objective materials with which to control his historical generalizations and interpretations.[1] It is, therefore, highly fortunate that the

[1] Cf. O. E. Neugebauer, *The Exact Sciences in Antiquity,* 2nd ed., Providence, Brown University Press, 1957, p. 1:

"The investigation of the transmission of mathematics and astronomy is one of the most powerful tools for the establishment of relations between different civilizations. Stylistic motives, religious or philosophical doctrines may be developed independently or can travel great distances through a

history of science has in the last few decades become a scholarly discipline in its own right, with its own specific methods, with a fair number of professional specialists, and with a respectable body of significant results.

It is perhaps only natural that the first epoch to be intensively studied by Western historians of science should have been that of ancient Greece, which at least since the Renaissance has been revered as the true source of Western civilization, especially in its secular aspects and more particularly in its ideal of rational knowledge. Already by the nineteenth century valuable research in the history of ancient Greek mathematics and astronomy had been accomplished. The culminating works of this period were Delambre's histories of ancient and medieval astronomy (1817, 1819)—by no means superseded even today. Of the vast amount of later work on ancient Greek mathematics and astronomy, the writings of J. L. E. Dreyer and Sir Thomas Little Heath may be singled out as especially comprehensive and authoritative.

Toward the end of the nineteenth century the great French scholar Paul Tannery (1843-1904), by his precept as well as by his practice, helped to revolutionize the study of the history of science with his broad outlook (he emphasized the necessity of investigating *all* branches of science together with their interrelations) and with his attention to detail (he emphasized the necessity of treating *all* the evidence by recognized historiographical methods).[2] Shortly after Tannery's time the first journals and the first national and international societies devoted exclusively to the history of science were established. It is worth pointing out that Tannery's demand for modern critical editions of important scientific texts has lost

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slow and very indirect process of diffusion. Complicated astronomical methods, however, involving the use of accurate numerical constants, require for their transmission the direct use of scientific treatises and will often give us very accurate information about the time and circumstances of contact. It will also give us the possibility of exactly evaluating the contributions or modifications which must be credited to the new user of a foreign method."

[2] See H. Butterfield, "The History of Science and the Study of History," *Harvard Library Bull.*, XIII, 3 (Autumn 1959), pp. 329-47.

little of its force today (Shakespeare has been so edited, but not Newton).

One most important result of twentieth-century research into the pre-classical civilizations of Egypt and Babylonia has been to modify somewhat the previous conception of ancient Greek science as a splendidly miraculous and isolated achievement not to be matched or even approached until its own "revival" stimulated the birth of modern science. (Even Dreyer and Heath need correction—or, at least, supplementation—on this score.) We have learned, for example, about the striking contributions to the exact sciences of the ancient Babylonians, going back as far as a millennium and a half before the Golden Age of Greece; and we now know that Greek science was indebted to Babylonian science for both mathematical methods and observational data. (The intricate historical affiliations between the science of the Babylonians and that of the Greeks is right now in the process of being elucidated by the work of O. E. Neugebauer and others.) Moreover, the picture of the middle ages as one long period of intellectual darkness unmarked by any significant scientific advances can no longer be seriously maintained (see the works by A. C. Crombie and M. Clagett in the Selective Bibliography for Vol. I). Especially in physics and cosmology will the often acute medieval discussions and controversies come as a surprise to students brought up to believe that modern physics was born in the fertile brain of Galileo. Pierre Duhem, himself a distinguished physicist, initiated in heroic fashion, almost singlehandedly, the modern study of the history of medieval science by the simple but effective expedient of reading and analyzing as many medieval scientific manuscripts as possible. Only five of the projected ten volumes of Duhem's *magnum opus, Le Système du monde* (subtitled "History of Cosmological Doctrines from Plato to Copernicus") had been published by the time of his death in 1916, but recently (1954-1959) the remaining five volumes have been published. (Dreyer's essay "Medieval Astronomy" in Vol. I is written in the form of a review of the first five volumes of *Le Système du monde,* but actually it constitutes an independent

contribution to the history of medieval astronomy.) It is now generally agreed that Duhem was a little too enthusiastic in his evaluation of medieval mechanics; the work of M. Clagett, E. Moody, and A. Maier is more objective in its approach.

The precise role of the middle ages in transmitting—and transforming—ancient science is a problem being actively investigated at the present time. The problem is highly complex owing to the multiple strands—Greek, Hindu, Persian, Islamic, Jewish, Latin—in the medieval scientific tradition. In the single field of astronomy, for instance, the historical situation has recently been summarized by O. E. Neugebauer as follows:

> We know today that Babylonian astronomy reached a scientific level only a century or two before the beginning of Greek astronomy in the fourth century B.C. The development of Hellenistic astronomy is largely unknown to us except for its last perfection by Ptolemy in the time of Hadrian and Antoninus Pius (probably completed shortly after 141 A.D.). Then, about three centuries later, Indian astronomy appears on the scene, deeply influenced by Greek methods, confronting us with the problem of transmission from West to East, a problem which is made particularly difficult by our ignorance about possible Persian intermediaries. Centuries later, under the Abbasids in Baghdad in the middle of the ninth century, Islamic astronomy begins, influenced from India as well as from Hellenistic sources. While the Greek component rapidly became dominant in the eastern part of the Muslim world, from Egypt to Persia, the outmost West retained in part methods of Hindu astronomy which left their traces as late as 1475 with Regiomontanus.[3]

A similarly confused pattern is repeated in medieval alchemy, medicine, and physics. Though the linguistic (and other) difficulties are truly formidable, the cultivation of the history of medieval science should yield a rich harvest: the very slowness of pace of

[3] O. E. Neugebauer, *The Transmission of Planetary Theories in Ancient and Medieval Astronomy*, New York, *Scripta Mathematica*, Yeshiva University, 1956, pp. 3-4.

medieval scientific progress may enable us to discern pervasive factors in the development of science which tend to be overlooked or minimized in the study of other periods (*e.g.*, the influence of tradition and, in particular, of educational modes and fashions, on the choice of scientific problems and the means available for solving them).

Until well into the nineteenth century the works of ancient Greek and Roman medical writers and their commentators were studied as textbooks of medicine. In this sense the history of medicine is very old, but the motivation for its study was at first more pragmatic than antiquarian. With the radical innovations in medicine that characterized the later nineteenth century the study of older medical ideas became a genuinely historical discipline, and at about this time several short-lived journals dealing with the history of medicine were published. The modern systematic approach may be said to have been inaugurated by the work of Karl Sudhoff (1853-1938), the great German historian of medicine. He devoted special attention to one key Renaissance figure, the physician and alchemist Paracelsus (c. 1493-1541), whose works Sudhoff edited and whose biography he wrote. Subsequent intensive research into the history of medicine has yielded many fascinating results, not least the discovery of profound connections between medicine and alchemy, astrology, religion, philosophy, and the arts.[4] Not only in the Renaissance but early in its development alchemy seems to have become closely associated with medicine. The tremendous com-

[4] See for example, O. Tempkin, "Medicine and Graeco-Arabic Alchemy," *Bull. Hist. Med.*, XXIX, 2 (1955), pp. 134-53; William S. Hecksher, *Rembrandt's Anatomy of Dr. Nicolaas Tulp; an iconological study*, N. Y. Univ. Press, 1958; W. Pagel, "Giordano Bruno: The philosophy of circles and the circular movement of the blood," *J. Hist. Med.*, VI (1951), pp. 116-124; also the two articles cited in n. 17 to Pagel's article in Vol. II.

Similar studies of ancient and medieval herbals may suggest important interrelations of botany, pharmacy, and the art of illustration. See C. Singer, "The Herbal in Antiquity and Its Transmission to Later Ages," *J. Hellenic Studies*, XLVII, Part 1 (1927), pp. 1-52; Wilfred Blunt, *The Art of Botanical Illustration*, London, Collins, 1950; *Art and Pharmacy*, ed. Wittop Koning, Deventer, Holland, 1950.

plexities and obscurities of the alchemical tradition are only beginning to be clarified, although as early as 1888 M. Berthelot edited (with French translations) what remains today the fundamental collection of ancient Greek alchemical texts. The astrological tradition has been the subject of close study by the Warburg school of art historians, and some of their work has direct implications for the history of science.[5]

The essays in these two volumes cover a wide range in space and time: from ancient Babylonia (c. 1500 B.C.) to the European Renaissance (c. 1400-1600 A.D.). Taken together, the essays provide a rough delineation of the principal features of the Western scientific tradition. (Notice that this tradition is not exclusively European in character: Babylonians, Arabs, and Hindus made vital contributions.) The sciences treated include mathematics, astronomy, physics, chemistry and alchemy, biology, and medicine. The essays also serve as admirable introductions to more detailed discussions of some of the principal topics in the history of ancient, medieval, and Renaissance science (say, ancient Greek mathematics or the medical work of Galen or Arabian alchemy or medieval mechanics or the astronomy of Kepler). The selective bibliography at the end of each volume is designed to facilitate further exploration of these topics.

Almost all the essays represent authoritative historical interpretations in the sense that they have been written by leading modern scholars, each with a first-hand knowledge of the relevant source materials in his special field. Naturally, one should expect neither a uniformity of approach, nor a perfect convergence of evaluations, nor even complete agreement on matters of factual detail. Indeed, the principal advantage of such a collection as this over a single author's "synthesis" lies in the diversity of approaches, the occa-

[5] See F. Saxl, *Lectures,* 2 vols., London, The Warburg Institute, University of London, 1957. On the relations between astrology and astronomy, see O. E. Neugebauer and H. B. Van Hoesen, *Greek Horoscopes,* Philadelphia, The American Philosophical Society, 1959. See also W. Hartner, "The Mercury Horoscope of Marcantonio Michiel of Venice," *Vistas in Astronomy,* Vol. I, ed. A. Beer, London & New York, Pergamon Press, 1955.

sional clash of interpretations, the final sense of vast problems yet unresolved and of countless facts awaiting discovery.

The reprinting of two essays by Henry Morley requires perhaps a few words of explanation. Morley (1822-1894) was not a historian of science but rather a historian and critic of English literature, with the wide-ranging intellectual interests and unbounded curiosity characteristic of many nineteenth-century British men of letters. He practiced medicine in his youth, which may explain his interest in Vesalius and Gesner; later he became one of the early promoters of the publication of cheap editions of the classics. Because his essays on Vesalius and Gesner (like his biographical triptych of the sixteenth-century scholars, Bernard Palissy, Jerome Cardan, and Cornelius Agrippa) are based on a close study of the primary sources, they are still worth reading. (Incidentally, one remark by Morley which "dates" the Gesner essay is that disparaging the medical virtues of cod-liver oil!)

Morley is not always as tentative and guarded in his conclusions as most modern scholars would want to be. Thus, the evidence is by no means conclusive (as Morley implies) that Jan van Kalkar was the artist responsible for the anatomical illustrations to Vesalius' books. It seems more likely that several artists (including Kalkar), all pupils of Titian, participated in the work of illustration. Also, Morley represents Vesalius as a determined iconoclast, vehemently opposed to the Galenical anatomy, whereas the more reasonable view today would seem to be that Vesalius claimed only to be correcting important details of a system which, as a whole, he accepted.[6] This view of Vesalius' attitude toward Galen is confirmed by what we now know to have been the general character of sixteenth-century science, namely, both traditional and revolutionary, strongly influenced by older religious, philosophical, and scientific systems but also committed to the new quantitative and

[6] See the introduction to the book by Saunders and O'Malley listed in the Selective Bibliography for Vol. II. Also, for a recent discussion of Gesner, see E. W. Gudger, "The five great naturalists of the sixteenth century: Belon, Rondelet, Salviani, Gesner and Aldrovandi: a chapter in the history of Ichthyology," *Isis*, XXII, 63 (1934), pp. 21-40.

dynamical approach to the study of natural phenomena. Harvey, van Helmont, and Kepler provide three of the most striking instances of this transition to modern science.

Philosophically, Harvey was a Peripatetic, van Helmont a neo-Platonist, and Kepler a neo-Pythagorean; all, however, broke radically with tradition by introducing mathematical methods into their respective fields: Harvey's decisive argument for the circulation of the blood hinges on his computation of the rate of flow of the blood from the heart; van Helmont made some of the earliest studies of weight relations in chemical changes; Kepler attempted (unsuccessfully) to formulate mathematically the force which holds the solar system together. With the work of these three men modern science, somewhat disguised by the remnants of various older traditions, had emerged.

Chicago
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Ancient Science

Solomon Gandz

A FEW NOTES ON EGYPTIAN AND BABYLONIAN MATHEMATICS* †

I. THE STATE OF CIVILIZATION IN GENERAL IN BOTH COUNTRIES

1 *Religion and Political Organization*

Scholars seem to be agreed upon the thesis that ancient Mesopotamian civilization was on a higher level, of greater antiquity and originality than the Egyptian civilization. The flowering of Egyptian civilization commenced about 3000 B.C. with the establishment of the Ancient Kingdom, and the assumption is that it was, partly and in some way at least, due to strong influences exercised by the older and much higher civilization of the Euphrates valley.[1]

* Reprinted from *Studies and Essays in the History of Science and Learning Offered in Homage to George Sarton,* edited by M. F. Ashley Montagu (New York, 1946), pp. 453-62.

† Abbreviations used in references:

CANTOR. M. Cantor, *Vorlesungen über die Geschichte der Mathematik,* Vol. I, 3rd ed., Leipzig-Berlin, 1922.

CHACE. A. B. Chace, *The Rhind Mathematical Papyrus,* 2 vols., Oberlin, Ohio, 1927-1929.

MMP. The Moscow Mathematical Papyrus, edited by W. W. Struve in German under the title *Mathematischer Papyrus . . . in Moskau* in QS A I, Berlin, 1930.

PEET. See RMP.

QS. *Quellen und Studien zur Geschichte der Mathematik etc.,* published by Springer, Berlin, 1930. . . .

RMP. *The Rhind Mathematical Papyrus,* edited by T. E. Peet, London, 1923.

STRUVE. *The Moscow Papyrus,* see MMP.

[1] See Albright, *From the Stone Age to Christianity* (Baltimore, 1940), pp. 100f, 114, 315, note 35; S. Smith, *Early History of Assyria* (London, 1928), p. 53.

When we compare the politico-religious organization of Babylonia at about 3000 B.C. with that of proto-dynastic Egypt, we immediately realize the pronounced superiority of the former to the latter. "Whereas Egypt was broken up into dozens of districts . . . Babylonia was divided into a relatively small number of city states. . . . The country as a whole was therefore more compact and there was much less cultural and religious particularism. The gods worshipped in one place were generally also recognized in the adjacent towns." [2] In order to conquer the whole country and command general recognition the Sumerian gods had to rise to a higher standard of power, justice, spirituality and universality. "Sumero-Accadian polytheism was much more clear-cut and consistent than was contemporary Egyptian." "Tribal or national henotheism does not seem to appear in any cuneiform religious sources from our age (3000-1600). On the contrary, the cosmic gods of Mesopotamia were naïvely and unquestioningly believed to rule the entire world, each in his own designated sphere or function. . . . Whereas in early Egypt . . . nearly all the gods are definitely associated with special animals or plants, there is hardly a single clear case in Sumerian Babylonia. . . . Sumerian deities are nearly always anthropomorphic." [3] On the whole, therefore, Sumero-Accadian religion impresses us as belonging to a more advanced stage of human thought and civilization.

2 *Language*

During the three centuries reaching from *c.*1500 till 1200 B.C. the Accadian tongue became the *lingua franca,* the diplomatic language of the whole Near East and even of the Egyptian empire. If an Egyptian king of that time wanted to correspond with the kings of Babylon and Assyria, or even with the governors of his own Syrian and Palestinian provinces, he had to avail himself of the

[2] See Albright, *loc. cit.,* pp. 140-141.
[3] Albright, *loc. cit.,* pp. 140, 143.

Babylonian tongue and script, and it was in the same tongue and script that the rulers of Mesopotamia and the Canaanite officials replied to him. The Aryan princes of Mitanni, in northern Mesopotamia, used the Babylonian language and the cuneiform script for their despatches and treaties. The Hittites of Anatolia discarded their old and clumsy hieroglyphs and adopted the Babylonian cuneiform signs for their own language; their treaties with Egypt, however, were drawn up in the Babylonian language.[4] At the capital of Amenophis IV in Egypt there has been found in a private house an interesting historical text composed in the Babylonian language and telling the story of the exploit of King Sargon of Agade (*c*.2530 B.C.). The text dates from the fourteenth century B.C. and the curious feature about this Babylonian text that was found in Egypt is that it is almost certain that it was written by a Hittite scribe. We thus discern in the fifteenth-thirteenth centuries the symptoms of a cosmopolitan age with an international tongue. There is a Hittite scribe who lives in Egypt and prepares a copy of a Babylonian literary text dealing with the exploits of King Sargon of Agade.[5] It was justly remarked by S. Smith[6] that "throughout the course of history the extraordinary feature of the Semitic languages has been the willingness of aliens and immigrant people to use them, and finally to adopt them altogether, a feature which in some respects is shared by modern English. This power of a Semitic language to overwhelm other tongues was illustrated in Babylonia by the final supremacy of Accadian over Sumerian." This linguistic victory won by the Babylonians was due not to their conquering armies but to their ascendancy in the peaceful arts, to far-flung commercial connections, to a highly developed industry and to an advanced civilization in general. These are the forces to which people submit voluntarily. Even the mighty Egyptian kings had to recognize the ascendancy of the Babylonian tongue.

[4] See L. W. King, *History of Babylon,* London, 1915, p. 1.
[5] See S. Smith, *Early History of Assyria,* pp. 83-84.
[6] *Loc. cit.,* p. 113.

3 *Writing*

The Egyptian hieroglyphs are an offshoot of the pictorial art, says Alan H. Gardiner in his *Egyptian Grammar.*[7] Originally, the Egyptians used only pictorial ideograms, the real pictures of things, in order to represent the objects which they wanted to describe. In the course of time, however, certain pictures were also used to denote the sounds of the words which served as the names of the things. They thus assumed a phonetic value and could be employed to denote other things which had the same name. For instance, the "mouth" is in Egyptian *ra,* hence the picture of the mouth was also used to signify the letter *r; kha* in Egyptian means a lotus-plant and is also the word for "thousand," hence the Egyptians depicted an ox and a lotus-plant in order to convey the meaning of "1000 oxen." However, the Egyptians never undertook it completely to replace the pictorial elements by the sound-elements. Throughout the history of their literature the Egyptian hieroglyphic script retained its character of a pictorial script eked out by some phonetic elements, which were originally pictograms but acquired a secondary sound-value.

While the hieroglyphic signs of the Egyptians represent the more primitive pictorial phase in the history of writing, the Babylonian cuneiforms have reached us in the far advanced stage of conventional phonograms. True, the Babylonian cuneiforms, which were originally invented by the Sumerians prior to 3500 B.C., had also had at the time of their introduction the character of a pictorial script. However, the phonetic stage using the original rude depictions as conventional phonograms in the form of groups of wedges, has been reached very early and has been further developed and perfected by the Accadians who adopted these signs from the Sumerians and adapted them to the writing of their own Semitic language. As a matter of fact, we are told that even the earliest crude signs and wedges of the Sumerians are already so convention-

[7] See pp. 6-8.

alized that it would be impossible to discern their original pictorial character and meaning had not their meaning been already known from other sources. Thus far, we know of no example of the old Sumerian script of which we could assume that it had served as a model for the Egyptian scribe.[8] However, it has been established that the first written documents of Egypt are to be dated by a few centuries later than those of Mesopotamia. Moreover, in the latter country the successive paleographic stages are preserved and may still be followed step by step, whereas in Egypt the formative period of writing seems to have been very short, hence the art of writing appears to have been an adopted institution rather than a slow and natural development. In addition to that it has been demonstrated that the earliest signs of writing in Mesopotamia were derived from the designs on the cylinder-seals by a natural process of evolution, while in Egypt such a relationship is entirely missing. In view of all these facts and in view also of the commercial and cultural relations which are known to have prevailed between Egypt and Mesopotamia at the period under discussion, Speiser argues[9] that "it is logical to assume that Egypt acquired the idea of writing from Mesopotamia." As to the differences in the form and use of the signs, they would have to be explained by the marked differences in the art and language of the two countries.

This invention and perfection of the cuneiform script may be considered as one of the finest achievements of the Sumero-Accadians. Its relative excellency was soon recognized in the whole Near East. We have already mentioned that before the close of the fifteenth century B.C. the rulers of Mitanni had adopted the cuneiform script together with the Babylonian language and the Hittites had adapted the script to their own language. In the ninth century, so we are told by L. W. King,[10] "the Urartians, settled in the mountains of Armenia, adopted the cuneiforms as their national

[8] See L. W. King, *A History of Sumer and Akkad* (London, 1910), p. 329; Gadd in the *Encyclopaedia Britannica,* 14th ed., XXI, 553-554.

[9] In his paper in the Waldo G. Leland Volume, *Studies in the History of Culture* (Menasha, 1942), p. 62.

[10] *Loc. cit.*, p. 1.

script. Elam substituted for their rude hieroglyphs the language and characters of Babylon. Finally, in the sixth century the Achaemenian kings invented a cuneiform sign-list to express the old Persian language."

4 *Trade and Commerce. The Art of Warfare*

The basis for the flowering of the arts and sciences is political stability and a prosperous civilization. This was the outstanding feature of the age of about 2100-1900 B.C. Commerce and industry flourished in the Babylonian country and a lively and profitable traffic was maintained with Syria and with Cilicia and Capadocia where there was at that time an important metal industry in existence. It is an established historical fact that there existed trade connections between India (Mohenjo Daro) and Babylonia at the early period of about 2900-2700 B.C. This must have given a great impetus to the development of the arts and crafts in Babylonia. The assumption is that the Mesopotamian craftsmen were superior to their contemporaries in Egypt, that trade connections existed between the Persian Gulf and the Red Sea in the early Sumerian period and that, as a result, certain Egyptian artists of about 3000 B.C. fell under Babylonian influence.

In those early times the Sumerians were already well trained and far advanced in the art of warfare. The chariot, a military weapon of which the Egyptians were ignorant before the Hyksos invasion, was already known to the Sumerians in southern Babylonia and used in their wars at the time of the first dynasty of Ur (*c.*2900 B.C.). The phalanx, with which the Greeks became acquainted in the fourth century B.C., was familiar to the Sumerian warriors of about 2800 B.C.[11]

[11] See S. Smith, *Early History of Assyria*, pp. 58, 50-51 and 53.

II. A COMPARISON OF BABYLONIAN AND EGYPTIAN MATHEMATICS

5 *The Superiority of Babylonian Notation, Arithmetic and Algebra*

In 1923, when T. E. Peet published his edition of the *Rhind Mathematical Papyrus,* the large bulk of the mathematical texts of the Babylonians was not yet known. It is therefore quite understandable that Peet should speak of the superiority of Egyptian mathematics to the mathematical knowledge of the Babylonians.[12] He even goes so far as to say that the complicated and awkward fractional calculations of the Egyptians reveal their superiority to the Babylonians. The fact, however, is that with regard to notation, arithmetic and algebra the Babylonians reached a stage of mathematical thought and training which leaves the Egyptians far behind them.

Egyptian notation is simple and primitive. There is a special symbol for each decimal order, hence there is no necessity for, and no trace of, the zero and place value. These two great inventions which are of fundamental importance for the whole structure of our modern notation were made by the Babylonians, who, in addition to that, had anticipated in their sexagesimal fractions the ingenious invention of the decimal fractions. In their system of notation, developed at about 2000 B.C., the Babylonians are therefore by thirty-five hundred years ahead of the Egyptians. The Egyptian methods of multiplication and division are extremely clumsy and awkward. They multiply by repeated doubling, using also occasionally the factor 10, and then they have to find out which multipliers must be added in order to obtain the original factor, and the added products yield the final result. Division is being performed by the method of trial and error: the divisor is being multiplied successively, by integers and fractions, till the dividend is obtained. The climax of clumsiness and futile complexity has been reached in their calculations with fractions, as may be seen by an examination of their so-called $\frac{2}{n}$ table and of the first forty examples of

[12] See his *RMP*, pp. 27-28.

the *RMP*. Moreover, the Egyptians had no definite rule for the choice of the common denominator. Frequently the largest number was chosen as the common denominator and some of the numerators are therefore mixed fractions.[13] We today must make great efforts, spend a great deal of energy and thought in order to grasp the meaning of their almost absurd methods of procedure. In the solution of the linear equations they are availing themselves of the primitive method of false position. The Babylonians, however, solve their equations according to the more advanced algebraic methods. In order to perform the operations of multiplication and division the Babylonians have only to look up the tables of multiplication, respectively also the tables for the conversion of common fractions into sexagesimal fractions. Finally, by the extension of the sexagesimal scale to the fractions and the presentation of the latter in the form of integers, the Babylonians have done away with the whole laborious system of the Egyptian fractional calculation.

In olden, primitive times man had to rely upon the organs of his body. He had to lift burdens and till the soil with his *hands,* to travel by *foot,* to store up knowledge in his *memory,* and to perform the simple mathematical operations with his *brains.* Civilization advances with the invention of tools. Machines do our work, books and encyclopaedias preserve our knowledge, symbols and formulae and tables think for us and perform our mathematical operations. The Egyptian scribe had to work hard and consume the energy of his brains in performing the most elementary arithmetical operations. The Babylonian mathematician had his tables and refined algebraic methods and formulae which helped him to do his work. He thus could rise to the higher levels of mathematical thought of which the Egyptian had no inkling. There is no trace of indeterminate analysis in Egyptian mathematics, while the Babylonians devoted a great deal of study to this subject. Of the mixed quadratic equations in their various Babylonian types with their ingenious

[13] See Chace, pp. 3-5, 9; Peet, p. 17f; cf. also Neugebauer in QS B I, pp. 329ff; Cantor, 1^3, pp. 71-72.

methods of solution the Egyptians had no knowledge, nor did they make an attempt at the formulation and solution of a cubic equation. In Bablyonian mathematics the theory of quadratic equations reached a high point of development and even the problem of cubic equations was tackled with vigour and intelligence.

6 *Pure Quadratic Equations in Egyptian Mathematics*

Literature: Gunn-Peet, *The Journal of Egyptian Archaeology,* XV (1929), 167-185; Struve, *The Moscow Papyrus,* No. 7, pp. 123-134; Neugebauer, *QS B,* I, 415 and 418; Vogel, *Die Algebra der Aegypter,* pp. 150-153, 161; Tropfke, *Geschichte der Elementar-Mathematik,* III³, 52 and 104f.

In Egyptian alegbra there are, thus far, no mixed quadratic equations of the type $x^2 \pm ax = b$, or of the other Babylonian types, to be found, but we have six problems leading to pure quadratic equations of the type $ax^2 = b$. These six problems occur in the *MMP,* nos. 6, 7 and 17; in the Kahun fragments and in the Berlin Papyrus 6619:

(1) *MMP,* no. 6: $x : y = 4 : 3$; $xy = 12$
Procedure: $y = \frac{3}{4}x$; $\frac{3}{4}x^2 = 12$; $x^2 = 16$; $x = 4$; $y = 3$.

Cf. no. 4 below where an identical problem occurs in the Kahun Papyrus.

(2) *MMP,* no. 7: A rectangular triangle: the area is $A = 20$; $x = \frac{5}{2}y$.
Procedure: $2A = 40$ (hence $xy = 40$); $\frac{5}{2}y^2 = 40$; $\frac{5}{2} \cdot \frac{5}{2}y^2 = \frac{5}{2} \cdot 40 = 100$; $(\frac{5}{2}y)^2 = 100$; $\frac{5}{2}y = 10$; $10 : \frac{5}{2} = 4$; $y = 4$; $x = 10$.

We have here an ingenious transformation of both sides of the equation into squares. This was not noticed by Struve. The identical problem is repeated in

(3) *MMP,* no. 17: A rectangular triangle: the area is $A = 20$; $y : x = (\frac{1}{3} + \frac{1}{15}) : 1$ (hence $y : x = \frac{2}{5} : 1$; $y = \frac{2}{5}x$).

Procedure: $2 \cdot 20 = 40$: $\frac{2}{5}x = y$; $xy = 40$; $\frac{2}{5}x^2 = 40$; $x^2 = \frac{5}{2} \cdot 40 = 100$; $x = \sqrt{100}$; $x = 10$; $y = 4$.

Here the equation is solved according to *x*, while in no. 7 it is solved according to *y*.

(4) Kahun Papyrus: The volume of a parallelopiped is $V = 120$; the height, $h = 10$; hence the base, $A = xy = 12$; $[y = \frac{3}{4}x]$.
Procedure: $\frac{3}{4}x^2 = 12$; $x^2 = 12 : \frac{3}{4} = 16$; $x = 4$; $y = 3$.

(5) Berlin Papyrus: $x^2 + y^2 = 100$; $y = \frac{3}{4}x$.
Procedure: $x^2 + \frac{9}{16}x^2 = 100$; $\frac{25}{16}x^2 = 100$; $\frac{5}{4}x = 10$; $x = 8$; $y = 6$.

(6) Berlin Papyrus: Not well preserved. Restoration by conjecture. $a^2 + b^2 = 400$; $a = 2x$; $b = \frac{3}{2}x$.
Procedure: $4x^2 + \frac{9}{4}x^2 = 400$; $\frac{25}{4}x^2 = 400$; $\frac{5}{2}x = 20$; $x = 8$; $a = 16$; $b = 12$.

7 *The Superiority of Egyptian Geometry*

It must be admitted that the Egyptian mathematician excelled in the field of geometry and was in many respects superior to the Babylonian. The high points of achievement in Egyptian geometry are as follows:

(1) While the Babylonians have always figured $\pi = 3$, the Egyptians have developed the formula:
$\frac{\pi}{4} = (\frac{8}{9})^2$; hence $\pi = \frac{4 \cdot 64}{81} = (\frac{4}{3})^4 = \frac{256}{81} = 3.1605 \ldots$
If a square has the side *d*, the area of the square is $= d^2$, and the area of the inscribed circle with the diameter *d* is $= (\frac{8}{9}d)^2 = r^2 \cdot 4 \cdot (\frac{8}{9})^2$ [14]

(2) The surface of the hemisphere is $= 2d^2(\frac{8}{9})^2$, which corresponds to the correct value $2r^2\pi$; see *MMP*, Problem 10. It must, however, be remarked that this is so only according to the interpretation of Struve. Peet, however, suggested an interpretation of the text according to which the problem would not deal with the hemisphere at all, so that there would re-

[14] See *RMP*, Problems 41-43, 48, 50.

main no foundation for Struve's theory.[15] N. considers Peet's interpretation as more plausible than Struve's.[16]

8 *Conclusion*

In his work *From the Stone Age to Christianity* (pp. 146-147) Albright summarizes his survey of Egyptian and Babylonian civilization with the following words: "The union, stability and prosperity brought to Babylonia by Hammurabi about 1760 B.C. made it possible for scholars to devote themselves to learned pursuits with a single-mindedness and a continuity heretofore unknown. The following two centuries saw an extraordinary development of empirical scientific and scholarly interest as is illustrated by many works on philology, lexicography, astronomy, mathematics and numerous branches of magic and divination. . . . While the Babylonians of this age did not equal their Egyptian contemporaries in their literary and rhetorical sophistication or in their knowledge of practical engineering and medicine, they surpassed them notably in less useful, but more intellectual pursuits."

A thorough investigation and comparison of Egyptian and Babylonian mathematics has shown that the Egyptians did indeed excel in practical mensuration, while the Babylonians were by far superior in notation, arithmetic and algebra, branches of mathematics which must be characterized as more intellectual than mensuration. On the other hand, we have also noticed that the Babylonians did surpass the Egyptians in the fields of religion, language and writing, and in some of their industrial and warlike arts. Owing to the wide diffusion of their tongue and script the Babylonians must also have by far surpassed the Egyptians in the international influence of their culture in general.

In his interesting paper on "Ancient Mesopotamia and the Be-

[15] See *The Journal of Egyptian Archaeology*, XVII (1931), 100-106, 154-160.

[16] See *QS B*, I (1930), 424, 428; Neugebauer, *Vorgriechische Mathematik*, pp. 129-137.

ginnings of Science"[17] Speiser compares the achievements of the two oldest cultural centers, Egypt and Mesopotamia, and arrives at the conclusion that Mesopotamia, which was distinguished by a relatively democratic organization of society, may be considered "the oldest center of scientific observation permanently recorded." This scientific activity included such fields as jurisprudence, the mathematical and natural sciences, and especially the linguistic studies. The flowering of the linguistic sciences is to be ascribed to the bilingual foundation of the Sumero-Accadian culture. In the course of time Sumerian became a dead language but the Semitic-speaking Accadians continued to cultivate it as the holy language of religion and learning. Thus a deep-rooted respect for scholarly tradition developed which led to the phenomenal achievements in the field of linguistics. On the other hand, the scientific achievements of authoritarian Egypt were inferior in scope as well as in degree. "Although notable in selected fields, such as medicine and engineering, it lacked the breadth and balance manifested in contemporary Mesopotamia."[18]

[17] First published in the *Studies in the History of Science*, University of Pennsylvania Press (Philadelphia, 1941), pp. 1-11, and later in a somewhat revised and expanded form in the Waldo G. Leland Volume, *Studies in the History of Culture* (1942), pp. 51-62.
[18] See the Leland volume, pp. 51-52.

O. E. Neugebauer

EXACT SCIENCE IN ANTIQUITY*†

If history is the study of relations between different cultures and different periods, the history of exact science has a definite advantage over general history. Relations in the field of science can be established in many cases to such a degree of exactitude that we might almost speak of a "proof" in the sense of mathematical rigor. If, for instance, Hindu astronomy uses excenters and epicycles to describe the movement of the celestial bodies, its dependence on Greek astronomy is established beyond any doubt; and the dependence of Greek astronomy on Babylonian methods is obvious from the very fact that all calculations are carried out in sexagesimal

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† In this paper I have, very much against my general principles, refrained from giving any kind of references. The simple bibliographical collection of texts, papers, and books consulted would require about the same space as the text of this paper; and even such a bibliography would be of very restricted use for the reader without often very long discussions in order to justify the special conclusions drawn here. I am still hoping to publish lectures on ancient astronomy which will discuss in detail problems which are touched here. [*The Exact Sciences in Antiquity* was published in 1951; second revised edition in 1957.—ED.]

notation. However, the fact that the center of interest in the history of science lies in the relationship between *methods* requires a new classification of historical periods. In the history of astronomy, for instance, concepts such as "ancient" or "medieval" make very little sense. The method and even the general mental attitude of the work of Copernicus is much more closely related to that of Ptolemy, a millennium and a half before, than to the methods and concepts of Newton, a century and a half later. It may seem, therefore, a rather arbitrary procedure in the following report on exact science in antiquity to take into consideration only the period before Ptolemy (ca. 150 A.D.). On the other hand, Ptolemaic astronomy climaxed the development of ancient science in its widest sense and we must therefore consider his work at least in a few lines, in order to be able to understand the influence of the preceding phases on all following development.

Ptolemy (ca. 150 A.D.) was undoubtedly one of the greatest scholars of all time. He left three large works, any one of which alone would place him among the most important authors of the ancient world: the *Almagest,* the *Tetrabiblos* and the *Geography.* The influence which these works exercised on the world-picture of medieval times can hardly be overestimated. Other works, such as his *Music, Optics,* investigations on sundials and geographical mapping, in addition to discussions on logic, theory of parallels, etc., show the extremely wide range of his interest.

This is not the place to discuss Ptolemy's works in any detail. It must be remarked, however, that the *Almagest,* for instance, shows in every section supreme mastership and independent judgment, even if he is presenting, as in many cases, results already obtained by earlier scholars. Furthermore, we must emphasize that the modern contempt for the *Tetrabiblos,* the "Bible of the astrologer," is historically very much unjustified. Today we know it to be an error to conclude any influence of the positions of the planets from the obvious influence of the position of the sun on the life on the earth. We must, however, not forget that the instrumental

facilities of ancient astronomy were by far insufficient to reveal any idea of the fantastic size of the universe. I, at least, can see no reason why, for example, the theories of earlier Greek philosophers, Plato included, are praised as deep philosophy in spite of the fact that they are hopeless contradictions to facts well known in their own time, while, on the other hand, an attempt to explain the difference between the characters of nations as the result of the difference in the respective inclination of the sun's orbit, the clima, should simply be disregarded as astrological error. The overwhelming historic influence of the *Tetrabiblos* can only be fully understood when we realize that this work is methodically the highest development of the first naturally simple world-picture of mankind, in which earth and universe still have a comparative order of magnitude.

The importance of Ptolemy's *Geography* is generally much more recognized. Hence we do not need to point out the rôle of this work for the knowledge of the inhabited world, but we should, on the contrary, direct our attention to the surprising inaccuracy of the geographical coördinates of almost all places. The method of determining latitude and longitude by astronomical means was known at least as early as Hipparchus (ca. 150 B.C.). The fact that his plan for exact mapping by astronomical methods could never be carried out in practice touches a very essential point in the general situation of ancient science. The determination of geographical longitudes requires the simultaneous observation of a lunar eclipse. All the details of this method are described in a book on optics written by Heron of Alexandria (first century A.D.), but Heron's example shows that not even for Rome were such observations available. Obviously the number of scholars in the ancient world was by far too small to undertake any kind of program based on systematic organized collaboration. One of the reasons for the rapid decline of ancient science lies in the fact that the deeper knowledge of science was then confined to an extremely small number of scholars.

A second element is equally important: the tendency to popularize science in accordance with the taste of the ruling class and to

adapt it to the teaching level of the schools. This tendency is clearly evidenced in the extant fragments of ancient scientific literature; I need only to mention the commentaries on the *Almagest* (Pappus ca. 320 A.D., Theon ca. 370 A.D.), the astronomical poem of Manilius (time of Augustus) or the purely descriptive geography of Strabo (same period), which entirely neglected the fundamental problem of exact mapping. Such works were well adapted to create a superficial kind of general education but ill suited for producing an atmosphere of serious research. There was almost nothing left to destroy when the collapse of the Roman Empire fundamentally changed the social and economic structure of the ancient world.

We have not yet mentioned mathematics outside of its applications in astronomy and geography. Actually we have to go back to the Hellenistic period in order to find that kind of mathematics which we have in mind when speaking about "Greek mathematics," and which is most clearly represented by Euclid's *Elements* (ca. 300 B.C.). This type of mathematics covers a very short period indeed, beginning in the time of Plato (Theaetetus and Eudoxus, ca. 400 B.C.), condensed in the *Elements* and appearing for the last time in the works of Archimedes and Apollonius (200 B.C.). The main reason for this early interruption of pure mathematics can be found in the purely geometrical type of expression which was adopted in order to gain the higher degree of generality which the geometrical magnitudes represent, in contrast to the field of rational numbers, which was the exclusive concern of oriental mathematics and astronomy. This geometrical language, however, very soon reached such a degree of complication that development beyond the theory of conic sections was practically impossible. As a result, the development of theoretical mathematics ended two centuries after its beginning, one century before the cultivated world became Roman.

I think that the influence of this pure mathematics on the general standard of mathematics in antiquity has been very much overestimated. Even Euclid's own works, other than the *Elements,* are

on a very different level; this can be simply explained by the remark that the *Elements* are concerned with a very special group of problems, mainly concentrated on the theory of irrational numbers, where the exactitude of definitions and conclusions is the essential point of the discussion. The main part of mathematical literature, however, was less rigorous and represented the direct continuation of Babylonian and even Egyptian methods. The Babylonian influence is, for instance, mainly responsible for the general character of other groups of Greek mathematical literature, as e.g., the work of Diophant (perhaps 300 A.D.). This situation in the field of mathematics corresponds very much to the general character of the Hellenistic culture, with its mixture of very contradictory elements from all parts of the ancient world. One of the most typical elements in this process is the creation of astrology, in the modern sense of this word, and of all kinds of mantic, number-symbolism, alchemy, etc., which became elements of highest importance for both Christian and Arabian thinking.

The different components in the creation of Hellenistic culture are especially visible in the field of astronomy. Mathematical astronomy can be traced back to Apollonius and, in much more primitive form, to Eudoxus. Both men were concerned with the development of kinematical theories for describing the movement of the celestial bodies. The lifetime of both of them is well known as a time of intimate contact between Babylonia and the Greeks. In particular, Apollonius was closely related to the rulers of Pergamon, at whose court one of the Babylonian astronomers, Sudines, well known from Greek sources, lived at the same time.

It is highly probable that this early Hellenistic astronomy was also the source of the Hindu astronomy, from which almost one thousand years later the Arabian astronomy originated. I think that this relationship between the Greek form of Babylonian astronomical computation and the older Hindu decimal number systems explains the creation of a decimal number system with place-value notation, which was transferred by the Arabs to Europe and finally became our number system.

The Babylonian mathematical astronomy which had so much influence on the Hellenistic science is in itself of very recent origin. Although no exact dates can be given, all available source material agrees with a date of about 300 B.C. for the origin of the earliest preserved theory of celestial motions. The most important feature of this late-Babylonian astronomy is its mathematical character founded on the idea of computing the very complicated observed phenomena by addition of single components, each of which can be treated independently. Here for the first time in history we meet the fundamental method for the investigation of physical problems by using purely mathematical idealizations, a method which determined the course of all future science.

Astronomy of this kind requires highly developed mathematics. Babylonian astronomy contains enormous numerical computations, which could never be carried out with such primitive methods as the Egyptian rules for calculating with fractions or the Roman and medieval abacus methods. Furthermore, every mathematical theory of celestial phenomena must fulfill conditions given by observations or, in other words, requires the solution of equations. The existence of such a mathematical astronomy would therefore be sufficient to justify the conclusion of the existence of corresponding Babylonian mathematics. Hence it is not in itself surprising that we actually have many mathematical texts in cuneiform script which show a development of mathematical methods to the point mentioned above. The surprising fact, however, is that these texts do not belong to the last period of Babylonian culture, as astronomy does, but that they appear as early as in the period of Hammurabi (the so-called First Babylonian Dynasty, about 1800 B.C.).

This leads to one of the most interesting groups of problems in the history of ancient science: Why does the origin of Babylonian mathematics precede the origin of astronomy? Why does such a mathematical astronomy appear at all, if not in direct development from mathematics? And finally: Why is there no parallel development in Egypt, where both mathematics and astronomy never went beyond the most elementary limits? In the following final section

I shall try to call attention to some of the conditions which may answer these questions by tracing some main lines of the development of ancient science in chronological order.

The very few old texts of mathematical character which we have from Mesopotamia belong to the latest Sumerian period, the so-called Third Dynasty of Ur (ca. 2000 B.C.). These texts are simple multiplication tables using the already fully developed famous sexagesimal number system. The most important feature of this system is the fact that the powers of sixty, such as 60 itself, or 3600 or 1/60th, and 1 are all denoted simply by "1." This notation makes multiplication or division as simple as in our method of calculation (or even simpler, because the probability of needing infinite fractions is smaller in a system having a base with more divisors). The introduction of this notation is doubtless not a conscious one but is the result of the influence of the monetary system, which was used for the notation of fractions in the same manner as in Roman times. In the beginning the different units were written with number signs of different size, but later this careful notation was omitted and thus the "place value" notation originated. This process is closely related to the economic development of this period, from which we have thousands and thousands of texts which carefully record the delivery of sheep, cattle, grain, etc., for the administrative offices. Hence the first and real decisive simplification in mathematical notations is merely due to the writing practice of generations of business scribes.

The next group of our source material comes from the First Babylonian Dynasty. Those texts are pure mathematical texts, treating elementary geometrical problems in a very algebraic form, which corresponds very much to algebraic methods known from late Greek, Arabian, and Renaissance times. The origin both of a mathematics obviously independent of direct practical needs and of its algebraic form can be explained by the same historical event, namely the complete replacement of the Sumerians by a Semitic population, although in very different senses. The main point is the

fundamental difference between the languages of the two types of populations and the fact that the Semites used the Sumerian script to express their own language. The Sumerian script operates with single signs for single concepts (so-called ideograms), derived from a picture script. The Semites used these signs in two different ways: first, in their old sense as representations of single concepts, and secondly, as pure sound symbols (syllables) for composing their own words phonetically. The first possiblity of expression corresponds in the field of mathematics exactly to our algebraic notation: instead of writing "length" by six letters, it is sufficient to write *l;* instead of writing "plus" or "addition," it is sufficient to use one sign $+$. We see here again how an entirely unconscious external influence caused the second fundamental invention of "Babylonian mathematics," the "algebraic" notation. Without such a deep linguistic difference such a powerful instrument as ideographic notation for mathematical operations would never have been introduced, as the parallel with Egypt clearly shows.

The second effect of this contrast between Sumerian and Semitic languages was the creation of systematical philological schools, whose existence is made evident by large collections of texts containing word lists, grammatical rules, etc. Exactly the same thing happened at the very same place in Arabian times, at the school of Baghdad. The new rulers had to study carefully the language and script, religion and law of the preceding culture. This school of language and theology created an atmosphere of general learning, supporting large numbers of well-educated scholars. In these circles Arabian mathematics and astronomy were created, and this corresponds certainly to the *milieu* for the origin of mathematics in the First Babylonian Dynasty.

There is no doubt that some kind of astronomy was cultivated in the same period. The unification of the many different local calendars of Sumerian times was accomplished under Hammurabi's rule, just as he reorganized preceding laws. The first lists of stars and the first rough observations of the disappearance and reappearance of Venus belong to this same period.

Babylonian history knows only short periods of comparative peace. The struggle with and between eastern and northern neighbors kept the country in continuous warfare for many centuries, until finally Assyria succeeded in constructing a powerful kingdom reaching from Persia to Egypt. Corresponding to this shift of power from southern Babylonia to Assyria we find an increasing interest in astronomy in Assyrian texts, where the astrological component, in particular, was developed, if not created.

The Assyrian empire paved the way for the Persian empire and its Hellenistic successors. Babylonia itself lost all political influence, but the cultural tradition was still extant and fully recognized in every part of the ancient world to which Assyrian influence reached. The world of Persian times, however, was very different from the world in the little country around the estuary of the Euphrates and the Tigris, in which Babylonian culture originated. Politically powerless, Babylon became an admired cultural center of a worldwide empire, comparable to the position of Rome in medieval times. The thousand-year-old uninterrupted tradition attracted the admiration of the younger cultures and created the myth of Babylonian wisdom; the main object of admiration was astrology, the "Chaldean" science, which opened inexhaustible new possibilities to religious speculation. Now Persian priests, Jews, and Greeks lived in Babylon, and an international idiom written in simple characters, the Aramaic, made general communication easy. Precisely this actually existing internationalism created competition between national cultures. Zarathustra, Abraham, and Pythagoras were each proclaimed as the inventor of all science and creator of astronomy, astrology, and number-wisdom, and each group asserted itself to be the oldest, and consequently, the teacher of mankind.

In this atmosphere of intellectual competition the Babylonian school of scribes and priests had to defend their authority. Thousands of texts of New-Babylonian, Seleucid, and Parthian times are the evidence of a Babylonian renaissance, returning even in linguistic aspects to old Sumerian traditions. This revival of intel-

lectual centers, this new intellectual activity, where Babylonian priests went to Asia Minor to teach their wisdom to the Greeks, resulted in the last period of Babylonian astronomy. The two mathematical achievements of the old Babylonian period, mentioned above, place-value-notation and algebraic symbolism, became the foundation of a theoretical astronomy of purely mathematical character which deserves more of our highest admiration the more we are able to understand its structure. This astronomy is not based on age-old observations of miraculous exactitude, as usually pretended, but on the contrary reduces the empirical data to the utmost minimum, mainly period relations, which are easy to observe and almost unaffected by the inexactitude of single instrumental observations. The enormous power of purely mathematical construction was fully recognized here for the first time in the history of mankind.

On the background of the remarks made at the beginning of this lecture we may perhaps resume our discussion with the statement that the development of exact science cannot be adequately described as a systematic step-by-step progress. In any case where we are able to disclose the conditions of essential new development, the contact between highly different cultures appears to give the initial impetus. On the other hand "culture" is in itself equivalent to tradition, which unifies large groups of populations into a common type of opinion and action. However, the same force, tradition, which defines a culture as an individual being, becomes an increasing impediment to further independent development and creates the long periods of "dark ages," which cover by far the largest part of all human history.

R. J. Forbes

METALS AND EARLY SCIENCE*

If we want to assess the effects of pre-classical and classical metallurgy on the growth of early science, we must realise that the basic processes of metallurgy were discovered almost entirely during the pre-classical period, that is before 600 B.C. The study of early metallurgy reveals that it passed through different stages. These phases are summarised in the following table:

EVOLUTION OF METALLURGY

I. Native metal as stones.
II. Native metal stage (hammering, cutting, etc.)
(copper, gold, silver, meteoric iron).
III. Ore stage (from ore to metal, alloys,
composition as primary factor).
(lead, silver, copper, antimony, tin, bronze, brass).
IV. Iron stage (processing as primary factor).
(cast iron, wrought iron, steel).

It will be clear that the two earliest phases can hardly be called metallurgy. Only native metal was treated and hardly recognised

* Reprinted from *Centaurus,* III, 1-2 (1953), pp. 24-31, with the permission of *Centaurus* and of the author.

to belong to a separate and peculiar class of "stones." Hence at first the usual wood- and stone-working techniques were applied, but finally some metallic properties played a part in this technique. These phases belong entirely to the prehistory of Europe and the Ancient Near East.

True metallurgy begins with the discovery of the "annealing" of native metals, which practically coincides with the important discovery of the melting and refining of copper and the smelting of oxide and carbonate copper ores. The latter two complexes of discoveries ring in the true Ore Stage, which covers what archaeologists usually call the Copper Age and the Bronze Age (their classification being based on the products of metallurgy rather than on the basic metallurgical processes themselves).

This true metallurgy, the recognition of the specific properties of metals and their ores, was born in the latter part of the fourth millennium B.C. in the Ancient Near East. The Ore Stage reached its full development when the smelting of sulphidic ores was discovered in the course of the third millennium B.C., probably in connection with the production of lead and silver from galena.

The Ore Stage covers the discovery of the production and refining of gold, silver, copper, lead, antimony and tin and their alloys. Technology profited most by the development of a series of bronzes with different tin content. Sometimes lead or antimony bronzes were used instead. This metallurgical phase was dominated by the production of alloys. Its specialisation by producing the appropriate alloy for each industrial purpose was intimately related with progress of refining technique, which allowed a more accurate dosage of the constituents than the earlier technique of mixing selected ores. The growing number of special alloys for different types of applications and the increasing quantitative accuracy with which the Bronze Age smiths progressively produced them are the indisputable proofs of this development. The composition of the metal or the alloy was the dominant factor in the production of the specific properties required in the tool or arm. Casting was

the dominant technique, which also promoted the remelting and recasting of waste metal.

During this Ore Stage the working of meteoric iron and of iron ores was attempted. But the end-product remained useless until an entirely new complex of techniques and processes had been discovered. This was achieved about 1400 B.C. in the north-east corner of Asia Minor. The new metal, iron (that is wrought iron with a steel surface-layer produced by carburising) soon conquered the world as the diffusion of its production was helped by fortuitous political circumstances. Invaders from the Balkans shook and destroyed the Hittite Empire of Asia Minor, dispersing many of the iron smiths over the whole of the Near East. They also adopted the new technique themselves, carrying it into Europe. Thus around 1000 B.C. the production of iron on a larger scale was well established in the ancient Near East and its adoption in prehistoric Europe began about the same time.

The study of early iron metallurgy reveals that the production of wrought iron and steel (here used throughout in the sense of surface-carburised wrought iron) entailed the introduction of an entirely different complex of techniques and processes. The Bronze Age smith had to relearn his trade. The new techniques involved correct slagging of the matrix of iron ores, new tools and methods to handle the "bloom" produced by the first smelting of iron ores, and the mastery of the carburising, quenching and tempering processes, which enabled the new smith to produce steel from wrought iron. For only the new steel was superior to bronze and similar alloys—wrought iron alone would not have produced this technical revolution.

It is clear from the above summary that in the case of iron the final product was not so much determined by chemical composition (that is by the carbon content of the iron) as by the processes to which the wrought iron was subjected after its production. The iron smith and his tools and techniques are those that spring up in our mind when we mention the word "smith." We think of his ham-

mer, bellows and anvil and no longer of the casting techniques of the Bronze Age smith. However, it should be realised that the full development of the Iron Age techniques was not reached before the beginning of our era.

The coming of the new metal, iron, made a lasting impression on the minds of the ancients. Not only did the meaning of metallurgical terms alter considerably—the Greek "chalkeus" originally a whitewright now came to designate a blacksmith. But far more important, the part played by metals in ordinary life was radically changed. Glover has aptly called the Bronze Age the age of princes and the Iron Age that of democracy. In the Ore Stage metals were not available in large quantities, mostly because the copper-hardening constituent, tin, could not be produced in sufficient quantities from the scarce and small deposits of tin-ores in the Near East. It had to be fetched from Cornwall, Bohemia or Spain and thus the use of bronze and its substitutes was restricted. On the other hand we must not judge from the archaeological finds alone, for much of the ancient copper and bronze was probably remelted and recast in Antiquity.

Iron was the first cheap metal produced by mankind, that was of general utility. It allowed the production of tools, weapons and armour for all instead of for princes and their retainers alone. The smaller workshops of the Bronze Age grew into important manufacturing centres in the Iron Age and stimulated the trade in ores and crude metals. Metallurgical skill was no longer restricted to the few but the number of smiths grew larger, mostly concentrated in the metallurgical centres. There arose strong guilds, which survived the crash of the Roman Empire.

Iron brought increased wealth to the craftsmen who made the tools and the arms for the many. Iron made living cheaper, for though corn prices are known to have risen in the earliest Iron Age, they fell rapidly soon after the political disturbances had quietened down. Only during the Hellenistic and Roman times did complications arise anew through the management of gold and silver currency, which brought back the "princes," and through the

control over the armouries which became one of the pillars of government of the Roman Empire.

However, it is not our purpose to sketch the social effects of metallurgy. We want to trace some of its important effects on early science and technology. The effects are particularly clear in the latter case. The smith was one of the earliest artisans whose craft was a full time job. He could only emerge in a society, where agriculture produced a surplus of food to sustain such crafts, that is in the proto-historic period of the later fourth millennium B.C.

It is clear that the rapid development of metallurgy in the Ore Stage both induced and was effected by a rapid specialisation of the smith. This specialisation is summarised below:

EVOLUTION OF THE SMITH

Primitive smith
from ore to finished product

miner
delving ores

metallurgist
processing ores

smelter
(ore to crude metal)

smith
(metal to mass product)

metal worker
(gold, silver, coppersmith)

Itinerant smith
gypsy, tinker

Copper and bronze metallurgy remained most important but the development of the production of lead, silver, gold, tin and antimony led to further specialisation after the early evolution of separate crafts of miners and metallurgists. In each of these groups of smiths special refining and production processes, tools and techniques were evolved which had a strong influence on technology

in general, however rudimentary real knowledge of the properties of metals might still be. We shall have occasion to point out the effects of metallurgical skill on the new art of alchemy.

The practical skill of these craftsmen and its influence on technology in general should not be underestimated. It also had great effects on the growth of the body of scientific knowledge. We must not forget that the very word metallurgy is derived from a Greek root metall-eia, "the delving for ores," which is closely related with metallao, "to search, to look for." We know that in the Ore Stage many itinerant smiths and prospectors travelled over the face of the Near East and Europe looking for surface deposits and veins of ore. Their trail can be followed by hoards or deposits of metal objects, cakes of crude metal, and cast-away material suitable for recasting. Their knowledge was of course restricted to the visible physical characteristics of metals and ores and to their behaviour in a few simple tests such as the "fire-test" and the reaction with acids like vinegar.

Yet at an early date such truly scientific data could be used by the Sumerians to classify natural objects on a sound basis. Though the terminology of metals and ores in other languages shows a similar selection of visible characteristics, it is especially pronounced in Sumerian nomenclature. The reason for this is the special agglutinative character of the Sumerian language. It enabled the ancient Sumerian prospectors and metallurgists to take a certain term for one class of minerals, say ^{a}ZA for stones in general. To this root-word suffixes and prefixes were added describing the special characteristics of sub-groups and individuals belonging to the same class according to this primitive classification. Adding "GIN" (blue) to "^{a}ZA" would give "^{a}ZA-GIN," that is "blue stone"; and "^{a}ZA-GIN-AŠ" would be "hard blue stone." A statistical evaluation of the texts in which such words occur in ancient Sumerian or Akkadian shows us that these characterisations are extraordinarily correct and usually allow us to give the proper modern equivalent.

The system of classification thus achieved by the ancient Sumer-

ians in the third millennium B.C. and later extended by the Akkadians shows much resemblance to that now used in organic chemistry. It proves that these early craftsmen made the most of such properties of metals and ores as they could observe with the simple tests at their disposal. This method of grouping of natural objects lived long. It was the basis of Theophrastus's systematic survey of minerals, called *On the Stones,* of later medieval lapidaries and of modern systems.

But a study of these characteristics of metals and minerals had further effects. It led to the earliest quantitative analysis of metals and alloys which we call "assaying." Assaying was developed by the goldsmiths and the metallurgists of the gold and silver mines.

As early as 1500 B.C. we read about cupellation tests made on natural gold and electrum (the native alloy of gold and silver). This test was developed into a production process for pure gold and silver (salt process and other variants) and was also the earliest quantitative laboratory test. The "fining pot" is commonplace in the Bible, Egyptian and Akkadian texts and was well known in classical times. Another analytical test was developed in Lydia. The touchstone was a black stone on which streaks of gold of known and unknown composition could be compared. These two tests, and especially the latter rapid one, were fundamental to the creation of coinage, which in its true "mint" form issued from Lydia to conquer the world and develop trade and thrift.

The influence of metallurgy went much deeper than this alone. The facts arising from the experience of the ancient smiths and some correlations among them were absorbed into the body of ancient pre-classical science. This became apparent as soon as the study of the structure of matter and the reaction of chemical compounds found its shape in the last-born science of Hellenism, alchemy.

In these early chemical texts we find the results of the absorption of metallurgical experience into the world-picture of the ancients. It is clear from much earlier religious, magical and other texts that the craft of the smith excited great interest and above all

awe from the earliest times onwards. It was known at an early date that meteoric iron came from Heaven. Names like AN-BAR and the Egyptian biꜣ-n-pt call it literally the "metal from heaven." However, most metals and minerals were known to be products of the earth. The smith was the craftsman who produced these metals from "stones that grew in the Womb of the Earth."

The earliest smith's craft was a mixture of ritual and technique. The sacred art of the "metal-doctor" was placed on the same level as that of the witch-doctor. In fact examples abound in folklore all over the world in which magical powers are ascribed to the smith. The expert who could transform stones into metal could not fail to be a master of the powers of the earth. For the "mana," the power of the Earth, was transferred not only to the metal but also to the smith himself and even to his tools. Purity and ascetism as well as the knowledge of the proper ritual were exacted from the smith performing his magical act.

The later alchemical belief in the sexuality of stones and metals goes back to this early metallurgy. For the new "charged stone," the metal, was born, and with birth the ancients coupled the idea of sexuality. Early Akkadian texts speak of "male" and "female" stones and metals. These different forms sometimes denote differences of texture or hardness.

More important was the early belief that stones and metal live in the womb of the Earth and there pass to perfection and even to death. The smith, who deprives these stones of their natural growth to perfection, somehow bypasses Nature's processes in his furnace and was thought to be able to obtain this perfect state by his magic. The natural evolution of the baser metals into silver and gold was part of his magic. This early transmutation lore passed into Hellenistic alchemy and was awakened in Arabic alchemy when kindred theories reached the Arabs from late Hellenistic and Far Eastern philosophy. The belief that stones and metals grew naturally in mines lived on until the nineteenth century and is probably still living in certain outposts of civilisation.

In early texts we find that the smith who tore these stones from

the womb of the Earth had to pay a penalty for this sin. He cancelled a paradisical state and changed "adamic" conditions. One life exacted another. Hence the Akkadian texts demand that an embryo be buried under the furnace to be built. This sacrifice of an abnormal birth fits into early belief. Was not the metal that the furnace produced itself an abnormal birth? The later alchemical tradition often considers the furnace as a vulva, as do many primitive smiths to this date.

The combination of these ideas and that of the sexuality of metals gives rise to the later theory of the male and female seed, represented by "mercury" and "sulphur" in Arab alchemy, which combine with the mineral to form the "child," the new metal. The ores or stones are considered to be the "genetrix" or "matrix" from which this child is born. Such ideas which can be traced in early metallurgical lore gave rise to the alchemical theories of the "marriage of metals" which is consummated in chemical combination. Other alchemical terms like "love" (combustion) and "death" (incineration) belong to the same class.

Still more features of early metallurgy appear in later alchemy. It is well known that the earliest alchemical reactions concern the colouring of metals. The reactions with these metals very often bear the same names as refining processes mentioned by the early metallurgists such as "cooking" (bašlu), "washing" (misû) or "roasting" (kalû). Ancient nomenclature of metals abounds with distinctions concerning the colours of different forms of one metal with varying amounts of contaminations. At least half of the sixteen different Akkadian terms for gold are connected with some hue or colour of native and refined products. These associations of metals with colours were blended with further associations of colours with the gods and their stars or planets; and thus the later astrological and alchemical linking of god, planet and colour came into being. Again these colours of metals play a large part in the attempts of the early alchemists to imitate them by the "kerotakis" and other processes.

Thus while the practical recipes and techniques of the early

smiths contributed to the development of technology in general, its magical and religious theory or background became part of the early pre-classical science. From that early science the strands lead us to alchemy, the youngest branch of science developed by the classical world. These beliefs stimulated the alchemists to enquire into the transmutations of metals and the reactions of chemical compounds, collecting data which, in the eighteenth century, helped to build our modern chemistry.

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Sir Thomas Little Heath

GREEK MATHEMATICS AND ASTRONOMY*

The history of Greek mathematics and astronomy, so far as we know it, begins with Thales, that is to say, in the sixth century B.C., a period later by a thousand years or more than the date of the substantial remains which we possess of the mathematics of ancient Egypt and Babylon, the two civilizations with which the Ionian Greeks came directly or indirectly into contact. We naturally ask, therefore, how much in the way of mathematics and astronomy did the Greeks learn from the Egyptians and Babylonians, what use did they make of it, and in what new directions (if any) did they develop it?

The question is best illustrated by the case of geometry, the subject in which the Greek genius won its greatest triumphs. The Greeks themselves traced the beginnings of their geometry to Egypt. Thales is said to have traveled in Egypt and to have brought geometry from thence. Most of what we know of Egyptian geometry is contained in the Papyrus Rhind and the Moscow Papyrus (the latter first published as recently as 1930). It consisted mainly

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of practical rules for measuring, more or less accurately, such areas as squares, triangles, trapezia and circles, and the solid content of measures of corn. The Egyptians also constructed pyramids of a certain slope by means of a certain ratio, namely that of half the side of the square base to the height. The use of this ratio implies the notion of similarity of figures, especially triangles. In the Moscow Papyrus there is actually a calculation, according to a formula which is absolutely correct, of the solid content of a frustum of a pyramid, given its height and the sides of the two square faces.

Now Thales, we are told, was the first to prove that a circle is bisected by its diameter. Other propositions attributed to him are: that the base angles of an isosceles triangle are equal; that if two straight lines cut one another the vertically opposite angles formed by them are respectively equal; and more of the same sort. Thales is said to have been the first to inscribe a right-angled triangle in a circle; which must mean that he was the first to discover that the angle in a semicircle is a right angle. We observe that here we have the beginnings of a theoretical geometry; and this brings us to the essence of the Greek achievement, which was the creation of mathematics as a science in and for itself. To make the transition from the rule-of-thumb mensuration practised by the Egyptians to geometry as a science, a complete change in the point of view was required, which the German philosopher Kant described as nothing less than "a *revolution,* brought about by the happy inspiration of one man." "A light," he says, "broke upon the first man who demonstrated the property of the isosceles triangle whether his name was Thales or what you will: after this the road that must be taken could no longer be missed, and the safe way of a science was struck and traced out for all time."

The idea then of proving propositions in geometry from the very beginning and developing the subject as a logical system was original with the Greeks. It is true that (as Dr. Neugebauer, the foremost of the leaders of research into Babylonian mathematics, says) proofs in the sense of the logical deduction of one result from another must have been part of the chain of steps which led

the Babylonians to the systematic solution of quadratic equations by rule; but it remains true that the Greeks were the first to consider the logical structure of a proof and the ultimate elements from which proofs must start, and they were the first to investigate theoretically the conditions under which the solution of a problem is possible or not.

As regards the principles of demonstration it would be difficult to find a clearer statement than that of Aristotle. Every demonstrative science, he says, has to do with three things, the subject-matter, the things proved, and the things from which the proof starts (ἐξῶν). It is not everything that can be proved, otherwise the chain of proof would be endless; you must begin somewhere, and you must start with things admitted but indemonstrable. These are, in the first place, principles common to all sciences, which are called *axioms* or *common opinions,* as that "of two contradictories one must be true," or "if equals are subtracted from equals the remainders are equal"; secondly, principles peculiar to the subject-matter of the particular science, say, geometry. First among the latter principles are definitions: there must be agreement as to what we mean by certain terms; secondly, we must assume the existence of certain things, e.g., in geometry, of points and lines, and in arithmetic of odd and even. Aristotle distinguishes carefully between definitions and hypotheses. A definition says nothing about the existence or non-existence of the thing defined; it only requires to be understood. If you assume that something exists or does not exist, this is a hypothesis. He also distinguishes between a hypothesis and what he calls a "postulate" (α'ἰημαΤ). A hypothesis is an assumption made with the assent of the learner; when an assumption is made and the learner either has no opinion on the subject or is of a contrary opinion, it is a "postulate." It does not appear that Aristotle would have described as "postulates" the five assumptions made by Euclid under that name; it seems probable therefore that the appropriation of the word "postulate" to describe these five assumptions was due to Euclid himself.

Besides laying down the principles, the Greeks invented the

methods used in geometry and gave them names. One method was the *reduction* of one problem to another, so that, if the latter was solved, the original one was *ipso facto* solved. The Greek term for *reduction*, ἀπαγωγή, seems to occur first in Aristotle, but instances of such reduction occurred long before. Next there is the method of mathematical *analysis* with its correlative *synthesis*. The method of *analysis* is said to have been "communicated" or "explained" by Plato to Leodamas of Thasos, but it must have been in use much earlier. The method of *reductio ad absurdum* is a variety of analysis. Aristotle describes this in various ways, as *reductio ad absurdum*, proof *per impossibile* or proof leading to the impossible. But here again the method was old. Zeno's paradoxes are a classical instance of it.

We pass to astronomy. The first indications of astronomical knowledge are found in the Homeric poems and Hesiod. They mention much the same stars or constellations, the Morning Star, the Evening Star, the Pleiades, the Hyades, Orion, the Great Bear, Sirius. Hesiod makes use of celestial phenomena for determining times and seasons in the year; he was acquainted with the solstices. But Thales counts as the first astronomer. Everyone knows the story of his falling into a well while star-gazing and being rallied by "a clever and pretty maidservant from Thrace" (as Plato has it) for being so eager to know what goes on in the heavens that he could not see what was in front of him, nay at his very feet. The traditions about the beginnings of Greek astronomy are of the vaguest; the *Doxographi* attributed to Thales, alternatively with others, some discoveries that he could not have made consistently with his ideas about the earth and the universe; what he knew he had probably learnt from the Babylonians either directly or indirectly through Egypt. Seeing the extent of the observations of the heavenly bodies which had been made in Babylon and Egypt through long centuries before the time of Thales, it is extraordinary that the early Greeks seem to have known so little about them. As early as the second millennium B.C. the Babylonians recognized the zodiac as the circle in which the planets move, and divided it

into signs of 30 degrees each. When, therefore, we are told by Pliny that Cleostratus of Tenedos (probably in the second half of the sixth century) "recognized the signs in it," it is a fair inference that Cleostratus brought from Babylon into Greece the knowledge of the zodiac and its twelve signs. The Babylonians discovered the period of 223 lunar months after which eclipses recur; and there can be no doubt that this became known to Thales and was the basis of his prediction of the solar eclipse which occurred in 585 B.C. during a battle between the Lydians and the Medes. About 1000 B.C. the Babylonians determined the time of day by means of a sundial consisting of an upright pointer one ell in length standing on a plane base; this instrument the Greeks called a *gnomon.* Another form of sundial had a pointer fixed upright in the middle of a hemispherical bowl; the Greek name of this was *polos.* According to Herodotus the Greeks obtained their knowledge of both these instruments and of the "twelve parts of the day" from the Babylonians. Anaximander is said to have set up a *gnomon* in Sparta and to have marked on it the solstices, the tropics, the seasons, and the equinox. The Babylonians made observations of the planets as early as the second millennium B.C. Apparently Venus was the first to be studied; there are Venus-tables based on observations made between 1921 and 1901 B.C.; Jupiter too and Mars were observed. The Egyptians knew a great number of stars or groups of stars, Sirius, Orion, the Great Bear, etc.; they also knew of the zodiac circle. The five planets were known in Egypt about the same date, say the thirteenth century B.C. Mars was called the Gleaming Horus; Venus was at first called the planet of Osiris and afterward the "Morning" and "Evening" Star, which suggests that the identity of the two was recognized. The Babylonians realized that the movements of the planets showed irregularities as compared with those of the sun and moon, though they do not seem to have discovered the stationary points and retrogradations. The Egyptians, however, observed the retrogradations in the case of Mars. When, therefore, we are told by Diogenes Laërtius that Pythagoras (or Empedocles) was the first

to observe that the Morning and Evening Stars are one and the same, and by Theon of Smyrna that Pythagoras was the first to observe that the planets appear to us to be carried through the signs of the zodiac in circles of their own, we are justified in supposing that the knowledge of these facts came to the Greeks from Babylon or Egypt. Thales is said to have discovered the inequality of the astronomical seasons and to have written on the solstice and the equinox; here too he may have been indebted to the Egyptians.

But the essence of the Greek contribution to astronomy is that from the first they began to speculate about the reason for all the phenomena; they wanted to explain the evolution of the universe and all that happens in it as a rational system. Anaximander, Thales's successor, put forward a bold hypothesis. Whereas Thales had made water his first principle, Anaximander made his, not water or any of the elements, but an undefined "Infinite" or "Unlimited" out of which the heavens and all the worlds could be generated. Out of it all the worlds arise and into it they must all pass away once more. At any one time there are an infinite number of worlds; some are coming into being, some are at their prime, some are passing away, "for existent things must pay the penalty and make reparation to one another for the injustice they have committed, according to the sequence of time." In the case of our world the portion of the Infinite which was detached to form it first separated into two opposites, the Hot and the Cold. The Hot appeared as a sphere of flame which grew round the air about the earth as the bark round a tree. Then the sphere was torn off and became enclosed in certain circles or rings, and thus were formed the sun, the moon, and the stars. The rings were a sort of circular hoops or tubes made of compressed and opaque air enclosing fire within them throughout but allowing the fire to be seen at one place only where there is a circular vent and the fire shines out, thus producing the appearance of the heavenly body. The circular tubes are supposed to revolve round some axis through the earth's centre, thus causing the apparent daily rotation. Anaximander boldly declared that the earth is suspended freely without support;

it remains in its position, he said, because it is at an equal distance from all the rest of the heavenly bodies; by this he clearly meant that the earth is in equilibrium. Plato expressed the same idea in the *Phaedo;* Aristotle explained it on the principle of indifference. According to Anaximander the earth is a short cylinder like a tambourine; one of its faces is that on which we stand, the other is opposite; its depth is one-third of its breadth. Anaximander was the first to speculate about sizes and distances; he said that the moon's "ring" is nineteen times the size of the earth, and the sun's ring 28 (or 27) times the size of the earth. The sun itself he held to be equal in size to the earth. Anaximander is famous also as having been the first to draw a map of the inhabited earth.

So much for the earliest Greek geometry and astronomy. What of their early arithmetic in comparison with the Egyptian and Babylonian? The Egyptian numeral system included separate signs for 1, 10, 100, 1000, 10,000, 100,000, and 1,000,000 each of which could be repeated up to nine times. The Papyrus Rhind gives us a fair idea of the Egyptians' technique; they showed great skill in manipulating their fractions, notwithstanding that they had no expressions for any fractions except submultiples (fractions with numerator unit) and $2/3$, and consequently whenever their work led to what we should write as an ordinary proper fraction (say $5/16$) they had to put it in the form of a sum of submultiples (or occasionally a difference) with or without $2/3$.

The Babylonians had separate signs for 1 and 10 but the remarkable thing is that as early as 2000 or 1800 B.C. they had a "position-value" system of numerals in which the scale is on the base 60 instead of 10, and it included, as well as the successive powers of 60, the successive sexagesimal fractions $1/60$, $1/60^2$ and so on, so that, if they wrote the equivalent of a row of figures like

$$14 \quad 28 \quad 10 \quad 6 \quad 4 \quad 9$$

it might mean 10 units *plus* 28 times 60 *plus* 14 times 60^2 and (on the right of the 10) 6 sixtieths, $4/60^2$ and $9/60^3$, respectively. This system had the inconvenience (compared with our decimal sys-

tem) that what corresponded to our single digits might be any number up to 59, and it was necessary to have a multiplication-table going up to 59 times 59; but, subject to this, it corresponded exactly to our decimal system (including decimal fractions). It is startling to find that such a system, with place-value and including sexagesimal fractions, was in regular use among the Babylonians many centuries before the *decimal* place-value notation was started by the Indians, and 3000 years or so before decimal fractions began to be used in the West (16th century). It is strange too that the Greeks seem to have had no knowledge of the Babylonian system until the astronomers began to use sexagesimal fractions in the second century B.C. and later.

The Greek alphabetical notation for numerals was an improvement on the Egyptian. It is not so convenient to work with as our decimal notation; but the Greeks evidently had no difficulty in carrying out their arithmetical operations, though actual early specimens of such working do not seem to have survived. Aristarchus of Samos and Archimedes deal with large numbers up to seven and eight figures; Archimedes extracts the square roots of such numbers and so on; but only the results are stated, not the detailed working.

To return to geometry. Between Thales and Pythagoras the record is a blank. We are told that Pythagoras transformed geometry into a liberal education, examining the principles of the science from the beginning and probing the theorems through and through in a purely intellectual manner. Aristotle says that the Pythagoreans were the first to apply themselves to mathematics and to advance the science. Pythagoras began with definitions, and his aim was obviously to build up the subject as a logical structure, with each proposition necessarily following as a consequence of the preceding propositions plus the original assumptions. The Pythagorean motto was

σχᾶμα καὶ βᾶμα ἀλλ' οὐ σχᾶμα καὶ τριώβολον

"a figure and a platform, not a figure and sixpence," which recalls

the story of Pythagoras having bribed a youth of good parts to learn geometry by promising to give him sixpence for each proposition that he mastered.

The theory of numbers too begins with Pythagoras. It took a quasi-geometrical form in the so-called figured numbers marked out by dots. If three dots be placed in a right angle about one dot we have a square (4); five dots placed round two sides of this square give the next square (9) and so on. The added numbers are the successive odd numbers 3, 5, 7, etc., and they were called *gnomons*, "gnomon" being the name used to describe the figure which when put round a given figure increases its size without altering its shape. If the odd number added to a particular square happens to be itself a square we have two square numbers the sum of which is also a square; and from this fact we easily derive the general formula (attributed to Pythagoras) for finding squares which are the sum of two squares. Other figured numbers were triangles, pentagons, hexagons, etc., each evolved by adding successive "gnomons" to 1 (dot). For triangles we add successively 2, 3, etc., the series of natural numbers. Placing four dots round one dot, so as to form with it the corners of a pentagon, we have a pentagonal number; seven dots have to be added to make the next pentagon, 10 for the next, and so on, the common difference of the successive gnomons being 3 which is 5 *minus* 2; for a hexagonal number the common difference of the gnomons is 4 which is 6 *minus* 2, and so on indefinitely.

Pythagoras is said to have discovered the theory of proportionals or proportion. This was a numerical theory which applied to commensurable magnitudes only; it was no doubt on the lines of Euclid's Book VII. Connected with proportion was the theory of means, and Pythagoras distinguished three of these, the arithmetic, geometric, and harmonic. He is said to have introduced from Babylon into Greece the "most perfect proportion"

$$a : \frac{a+b}{2} = \frac{2ab}{a+b} : b$$

where the second and third terms are, respectively, the arithmetic and harmonic means between *a* and *b*. A particular case is 12:9 = 8:6, and this bears upon what was probably Pythagoras's greatest discovery, namely that the musical intervals correspond to certain arithmetical ratios between lengths of string at the same tension, the octave corresponding to the ratio 2:1, the fifth to 3:2, and the fourth to 4:3. These ratios are the ratios of 12 to 6, 8 and 9, respectively.

In geometry Pythagoras is credited with the proof of the proposition, known as Euclid I.47, that in a right-angled triangle the square on the hypotenuse is equal to the sum of the squares on the other two sides. This naturally connects itself with Pythagoras's formula for finding two square numbers the sum of which is a square. The construction of the "cosmic figures" (as they were called) was also attributed to him. These are the five regular solids, the tetrahedron, the cube, the octahedron, the dodecahedron, and the icosahedron. (The discovery of two of them, the octahedron and icosahedron, is alternatively credited to Theaetetus who wrote on all five.) The faces of the dodecahedron are twelve regular pentagons, and the construction of the regular pentagon depends on a problem solved in Euclid II.11, that of dividing a straight line into two parts such that the rectangle contained by the whole line and the lesser of the parts is equal to the square on the greater part. This is a particular case of a general method known as the *application of areas*. This method, definitely attributed to the Pythagoreans, is absolutely fundamental in Greek geometry. The problem is to apply to a given straight line (as base), in a given angle, a parallelogram which shall be equal in area to any given rectilineal figure. In the more complicated cases the applied parallelogram, though applied to the given base, is required to overlap it or fall short of it by a parallelogram similar to a given one. The three cases taken together are equivalent to the algebraic solution of the general equation of the second degree provided that it has real roots. The simple case called παραβολή (application pure and simple) is solved in Euclid I.44, 45, the case of defect (called

ἔλλειψις) and that of excess (ὑπερβολή) in VI.28, 29; and here we have the origin of the names *parabola, ellipse,* and *hyperbola* given by Apollonius of Perga to the three conic sections.

The Pythagoreans thus devised two of the principal and most powerful methods in use in Greek geometry, those of proportions and application of areas. They also knew the properties of parallel lines and proved the theorem of Euclid I.32 that the three angles of any triangle are together equal to two right angles.

The Pythagoreans made another vital discovery, that of the incommensurable or irrational ("in no ratio"), which revealed itself in the relation of the diagonal of a square to its side. That the diagonal of a square is incommensurable with its side they proved by a *reductio ad absurdum* showing that, if the two are commensurable, it will follow that one and the same number is both odd and even. This proof is referred to by Aristotle and is still in use. But the discovery of the incommensurable was disconcerting because it made untrustworthy such proofs as depended on the Pythagorean theory of proportions, which was arithmetical; this would necessitate the substitution of new proofs in many cases. In the circumstances one can understand the story that the school tried in the first instance to keep the discovery secret and that one who divulged it perished by shipwreck or (as another version has it) was expelled and had a tomb erected for him as if he were dead. The difficulty was not overcome till Eudoxus in the fourth century discovered the great theory of proportion (later embodied in Euclid's Book V) which is applicable to all magnitudes whether commensurable or incommensurable.

Equally original was the Pythagorean astronomy. Pythagoras himself is said to have been the first to hold that the earth and the other heavenly bodies are spherical in shape. He realized that the sun, moon, and planets appear to have a motion of their own in a sense opposite to that of the daily rotation, but he seems to have retained the earth in the centre. His successors actually abandoned the geocentric theory and made the earth, like the sun, moon, and planets, revolve in a circle round the "central fire," in which were

supposed to reside the governing principles and the force which directs the movements in the universe. The Pythagoreans also assumed another body revolving round the central fire between it and the earth, but always accompanying the earth; this, like the central fire itself, was invisible to us because the hemisphere of the earth on which we live was turned away from it. Philolaus and one Hicetas of Syracuse are alternatively credited with this theory, the first step toward the Copernican hypothesis. It has quite recently been suggested that the central fire of the Pythagoreans was really the sun, and the "central fire" was a camouflage invented to save the innovators from a fate like that of Anaxagoras who narrowly escaped death for saying that the sun was a red-hot stone and the moon earth. It was Anaxagoras, too, who first declared that the moon receives its light from the sun.

The geometry I have spoken of so far belongs to the Elements. But before the body of the Elements was complete, the Greeks had advanced beyond the Elements. By the second half of the fifth century they had attacked three famous problems in higher geometry, the squaring of the circle, the doubling of the cube, and the trisection of any angle. The great names belonging to this period are Archytas, the friend of Plato, Hippias the sophist, Hippocrates of Chios, and Democritus.

Hippias of Elis, the sophist, is said to have claimed to possess all accomplishments. He lectured up and down the country. As a detail we are told that he got no fees for his lectures in Sparta; the Spartans could not endure lectures on astronomy and geometry; it was only a small minority of them who could even count. Hippias invented a certain curve described by a point which is the intersection of two straight lines moving simultaneously but with different motions (the one line turning uniformly about one end as centre, and the other moving uniformly and always parallel to itself). Hippias used this curve for the trisection of any angle or the division of any angle in any given ratio; it was afterward employed by one Dinostratus and Nicomedes for squaring the circle, whence it got the name τετραγωνίζουσα (*quadratrix*).

Hippocrates of Chios is mentioned by Aristotle as an instance to prove that a man may be a distinguished geometer but, at the same time, a fool in the ordinary affairs of life, because he had allowed himself to be defrauded of a large sum by customhouse officers at Byzantium. Hippocrates was, so far as is known, the first compiler of a book of *Elements;* he is also said to have proved that circles are to one another as the squares on their diameters (Euclid XII.2). He attacked the problem of the doubling of the cube and, though he did not solve it, he reduced it to another, namely that of finding two mean proportionals in continued proportion between two straight lines; it was in this form that the problem was afterward attacked and solved. Further there is preserved in Simplicius's commentary on the *Physics of Aristotle* an account taken from Eudemus's *History of Geometry* of a remarkable tract by Hippocrates on the *Quadrature of Lunes* (in Greek μηνίσκοι, little lunes or moons, i. e., crescent-shaped figures each formed by two arcs of circles). Hippocrates by very clever geometry squares three separate lunes of certain types (which are actually three out of the only five of the kind that *can* be squared by the geometry of the straight line and circle—the other two were apparently not squared till the 18th century A.D.). Hippocrates evidently hoped, by squaring such lunes, to lead up to the quadrature of the circle, and he actually squared the sum of a circle and a certain lune. Unfortunately the particular lune was not one of those which can be squared, so that the attempt to square the circle itself was abortive.

Democritus of Abdera (born 470 or 460 B.C.) was a philosopher of extraordinary range, so much so that he went by the name of "Wisdom" (σοφία). In his theory of atoms, common to him and Leucippus, he was the forerunner of the most modern researches on the subject. But he was also distinguished as a mathematician and astronomer. Diogenes Laërtius gives a long list of his works, which have unfortunately perished. In astronomy he wrote on the Planets, their order and relative speeds, on the Great Year, a Calendar, a Description of the Heaven, of the Pole, of the World, On the Water-clock. In mathematics he wrote on geometry, on

numbers, on irrationals, on contact with a circle and a sphere, this tract being no doubt concerned with the nature of the contact of a circle with a tangent to it, and of a sphere with a tangent-plane. We gather that this last was directed against views like those of Protagoras the sophist, who argued that no such straight lines or circles as the geometer assumes exist in nature and that a material ruler does not touch a material circle in one point only. Archimedes tells us that Democritus was the first to assert, though he did not prove, that the volume of a pyramid is one-third of that of a prism on the same base and of equal height, and the volume of a cone is similarly one-third of a cylinder on the same base and of equal height, theorems first proved by Eudoxus. The rigorous proof involves infinitesimal considerations.

Democritus, like Anaxagoras, held that all magnitudes are divisible *ad infinitum;* he even held that his atoms were in a mathematical sense so divisible. But he recognized the difficulties connected with infinitesimals, and he stated a dilemma about the cone quite comparable in force with the famous paradoxes of Zeno which cannot be said to have been finally disposed of even today. "If," said Democritus, "a cone were cut by a plane parallel to the base" (meaning a plane very close indeed to the base—the very next section, as it were), "what must we think of the surfaces forming the sections? Are they equal or unequal? For, if they are unequal, they will make the cone irregular as having many indentations, like steps, and unevennesses; but if they are equal, the sections will be equal and the cone will appear to have the property of a cylinder and to be made up of equal, not unequal circles: which is very absurd."

Zeno claimed to prove that motion is impossible by *reductio ad absurdum,* first on the assumption that magnitudes are divisible *ad infinitum,* and secondly on the opposite assumption that space and time are *not* divisible *ad infinitum* but are ultimately composed of indivisible elements; the Dichotomy and Achilles make the former assumption, the Arrow and the Stadium the latter. There is no doubt that Zeno's arguments profoundly affected the later course

of Greek geometry. They were thought to be fatal to such attempts to square the circle as that of Antiphon, the sophist. Antiphon's idea was to take an equilateral triangle or a square inscribed in a circle, then to inscribe a regular polygon with twice the number of sides, and so on continually, until (as he said) the area of the circle was used up by reason of the sides becoming so small as to coincide with the circumference of the circle. No, it was objected, this could never happen because the process would never end.

Geometry was saved from the impasse by the genius of Eudoxus (408-355 B.C.) who invented the so-called "method of exhaustion" for finding the superficial area or solid content of figures bounded by curved lines or surfaces. This method only requires that it shall be proved, e.g., in the case of the circle and the inscribed polygons that, by continuing the construction of Antiphon, we can make the inscribed polygon differ in area from the circle by *as little as we please*. The method of exhaustion became the one classical method of measuring curvilinear surfaces and solids. It was used by Eudoxus himself to prove the propositions discovered by Democritus about the volume of the cone and pyramid. It was used by Euclid, in his Book XII, to prove the same propositions, and also the propositions that circles are to one another as the squares, and spheres are to one another as the cubes, on their diameters, respectively. It is the method regularly used by Archimedes for more difficult cases, the area of a segment of a parabola, the surface of a sphere and a segment thereof, the content of segments of the solids of revolution obtained by making the three conic sections revolve about their axes, the paraboloid, namely, the ellipsoid and the hyperboloid.

In the meantime Archytas solved the problem of the doubling of the cube by solving the problem to which it had been reduced—namely the finding of two mean proportionals between two straight lines. This he did by a wonderful construction in three dimensions, determining a certain point as the intersection of three surfaces, a certain cone, a half-cylinder, and a *tore* (like an anchor-ring) with its inner diameter *nil*.

The theory of irrationals was carried further by Theodorus of Cyrene, Plato's teacher in mathematics, who proved that the side of a square containing 3 square feet, 5 square feet or any non-square number of square feet up to 17, is incommensurable with 1 foot. Theaetetus generalized this result and extended the theory by constructing and classifying certain more complicated irrationals.

The difficulties caused by the discovery of irrational straight lines in geometry, and the non-applicability to them of the Pythagorean theory of proportion, were overcome by the great theory of proportion again due to Eudoxus, which is set out in Euclid's Books V and VI, and which is applicable to all magnitudes alike whether commensurable or not.

Plato was an enthusiastic devotee of mathematics and astronomy: "let no one destitute of geometry enter" (ἀγεωμέτρητος μηδεὶς εἰσίτω), said the inscription over the door of his school. In astronomy he is said to have set it as a problem to all earnest students to find "what are the uniform and ordered movements by the assumption of which the apparent motions of the planets may be accounted for." It may have been in answer to this that Eudoxus put forward his brilliant hypothesis of concentric spheres. His solution was purely theoretical; he imagined for the sun and moon, respectively, a system of three spheres and for each of the planets a set of four spheres, all the spheres being concentric with the earth and rotating about different axes, one within the other. The poles about which each of the inner spheres rotate are fixed on diameters of the next enclosing sphere. The outer sphere is that of the daily rotation, the next revolves about the poles of the zodiac circle; the effect of the rotation of the third and fourth spheres is to make the planet describe on the second sphere a curve called the *hippopede* (horse-fetter) like an elongated figure of eight bisected longitudinally by the zodiac circle. The whole arrangement is a marvel of geometrical ingenuity.

A little later, Heraclides of Pontus, a pupil of Plato, made a great step in advance by declaring that the earth revolves about its

own axis in about 24 hours, the daily rotation of the heaven being only apparent, and that Venus and Mercury revolve about the sun like satellites. This was a partial anticipation of Aristarchus of Samos.

Menaechmus, a pupil of Eudoxus, who is said to have told Alexander the Great that "there is no royal road to geometry," is famous as the discoverer of the three conic sections, two of which, the parabola and the hyperbola, he used to solve the problem of the two mean proportionals, of which Archytas had given the first solution.

We come now to what has been called the Golden Age of Greek geometry. The three great names in this period are those of Euclid, Archimedes, and Apollonius of Perga. Euclid is, or rather was until recent years, almost a household word, in England at any rate; in the speech of most people it meant not a man but a book, the famous *Elements* of Euclid, which was a regular part of the curriculum in all schools and universities—so much so that I remember when once I spoke about Euclid to some person of ordinary education, he said "Euclid? I never knew he was a man, I thought he was a book!" He was a man, a kindly humane creature with a sense of humor as when, in a class, a student after learning the first proposition asked him "What shall I get by learning these things?" he called a slave and said "Give him sixpence, since he must needs gain by what he learns." Euclid's *Elements,* no doubt the greatest mathematical textbook of all time, immediately displaced all earlier collections of Elements, took its place with all Euclid's successors as the standard authority, and dominated the teaching of geometry for twenty-two centuries. It does not, however, only contain geometry: Books I to VI deal with plane geometry, Books VII to IX with the theory of numbers, Book X with incommensurables and irrationals, and Books XI to XIII with solid geometry, ending with the construction and properties of the five regular solids. Proclus says that "Euclid put together the Elements, collecting many of Eudoxus's theorems, perfecting many of Theaetetus's, and also bringing to irrefragable demonstration the things which were only

somewhat loosely demonstrated by his predecessors." No doubt this is a fair description; much of the subject-matter was pre-Euclidean, but the whole design, arrangement, and marshaling of proofs, were Euclid's own. He wrote also on higher geometry and the other mathematical subjects known in his day—the *Conics,* the so-called *Porisms,* and the *Surface Loci* belong to the first class; these are all lost, but we can judge of their contents by the accounts given of them by Pappus. To the second class belong the *Phaenomena,* a book on spherical astronomy, and the *Optics*—these survive in Greek. He also wrote on the elements of music.

Aristarchus of Samos, who is famous for having anticipated Copernicus, comes between Euclid and Archimedes; he was known as "the mathematician" and was a first-rate geometer. In his extant book *On the Sizes and Distances of the Sun and Moon* he practically finds, by pure geometry, limits to the values of certain trigonometrical ratios (sines and cosines) of certain very small angles, 3° and 1°.

Next comes Archimedes, a genius second to none in the whole history of mathematics; in any selection, say of the three greatest mathematicians that the world has ever seen, he would undoubtedly be included. He was born about 287 B.C. and was killed in the siege of Syracuse by Marcellus in the Second Punic War (212 B.C.). At the capture of Syracuse, which he had not even noticed, he was found by a Roman soldier intent on a diagram drawn on the ground, said to the soldier, "Stand away, fellow, from my diagram," and was immediately killed. Most persons know the stories about him—how he said, "Give me a place to stand on and I will move the earth" and how he for a long time foiled the attacks of the Romans on Syracuse by the clever mechanical devices and engines that he used against them. But he himself thought meanly of these things; all his interest was in pure mathematical speculation.

Archimedes carried pure geometry to the utmost limit of what it could accomplish in the absence of some entirely new method such as we have in analytical or coordinate geometry with its use of algebraical notation, which had not been invented in Archimedes's

time. He himself evidently regarded as his greatest achievement the finding of the surface and volume of a sphere; for he caused to be engraved on his tomb a representation of a sphere inscribed in a cylinder with height equal to the diameter, together with the ratio (3 : 2) which the cylinder bears to the sphere. Eudoxus and Euclid had proved that spheres are to one another, in volume, as the cubes of their diameters; Archimedes was the first to investigate the superficial area as well as the volume of a sphere, with the remarkable result that the ratio 3 : 2 applies not only to the volumes of the cylinder and inscribed sphere, but also to the surface of the cylinder *including its two ends* as compared with that of the sphere. In this case, as in many others, Archimedes's method amounts to a real anticipation of the modern "integral calculus"; among his results he finds the area of any segment of a parabola and of a spiral, the surface and volume of any segment of a sphere, and the volumes of any segments of the solids of revolution of the second degree, *i.e.,* the solids formed by making the three conic sections revolve about their axes, respectively. In one case dealing with the tangent to a spiral Archimedes uses considerations such as come in the foundations of the "differential calculus."

In arithmetic he calculated approximations to the value of what we call π, the ratio of the circumference of a circle to its diameter, in the course of which calculation he gives approximations to the square roots of large as well as small numbers. His *tour de force* in arithmetic is the *Sandreckoner* in which he finds the limit of the number of grains of sand which, on certain assumptions as to the size of the universe, the universe would contain. His result is the number which we should write as 10^{63}; it is interesting to compare this with the estimate of 10^{79} which Sir Arthur Eddington in *New Pathways in Science* arrives at as the number of protons, as also of electrons, in the universe. To express his results, which were quite beyond expression in the Greek numerical notation, Archimedes invented a system of arithmetical terminology by which he could denote in language any number up to that which we should write with 1 followed by 80,000 million cyphers. Whereas we use

the decimal notation, and the Babylonians used a scale with 60 substituted for 10, Archimedes's system amounts to substituting 100,000,000 for 10!

Archimedes wrote the first scientific treatise on mechanics (or rather statics) under the name of *Plane Equilibriums;* in this he not only worked out the principles of the subject, including the theory of the lever, and that of the centre of gravity, but he found the centres of gravity not only of rectilineal figures such as the triangle, parallelogram, and trapezium, but also of a parabolic segment, a semicircle, a cone, a segment of a sphere, and a right segment of a paraboloid and a spheroid of revolution.

Again, he originated the whole science of hydrostatics in his work *On Floating Bodies,* which again he carried so far as to give a complete investigation of the positions of rest and stability of a right segment of a paraboloid of revolution floating on a fluid with its base either upward or downward and either wholly above or wholly below the surface of the fluid.

Lastly he was famous as an astronomical observer and actually constructed what he called a "sphere," which was really a *planetarium,* a model of the heavens imitating the motions of the sun, moon, and planets. It was taken to Rome and placed in the temple of Vesta. Cicero saw it and says that it represented the periods of the moon and the apparent motion of the sun with such accuracy that it would even (over a short period) show the eclipses of the sun and moon.

Time compels me to cut short the rest of the story. The Golden Age of Greek geometry ends with Apollonius of Perga (about 265 to 190 B.C.) who was called the Great Geometer on the strength of his great work on *Conics* in eight books, four of which survive in Greek and three in an Arabic translation. He also wrote works in higher geometry; these are mostly lost, but we can gather some idea of their contents from descriptions of them by Pappus and others. In particular he wrote on a comparison of the dodecahedron and icosahedron inscribed in one and the same sphere, on the cochleas or cylindrical helix, on irrationals, and on the Burning Mirror,

dealing with spherical mirrors if not of paraboloidal mirrors also.

In astronomy he discussed the hypotheses of epicycles and eccentric circles, respectively, which had been put forward to explain the movements of the planets.

Eratosthenes, a younger contemporary and friend of Archimedes, is famous for a remarkably close estimate which he made of the size of the earth. Observing the difference between the altitudes of the sun at the summer solstice at noon at two different places, Alexandria and Syene, supposed to be on the same meridian, and knowing the distance between the two places to be 5000 stades, he calculated the circumference of the earth at 250,000 stades (later apparently corrected to 252,000 stades). On the most probable assumption as to the length of the stade, this gives for the diameter of the earth about 7850 miles, only 50 miles less than the true polar diameter.

After Eratosthenes we come to minor geometers who were mostly known as the inventors of special higher curves, Nicomedes of the conchoid or cochloid so-called, Diocles of the cissoid, and Perseus of the sections of what he called a spire (σπεῖρα), one variety of which is the *tore* or anchor-ring. The study, however, of higher geometry (except *sphaeric,* the geometry of the sphere) seems to have languished until that admirable mathematician Pappus arose (in the third century A.D.) to revive interest in the subject. His *Collection* (συναγωγή) is, after the original works of the great geometers, the most comprehensive and valuable of our sources for the history of Greek geometry.

A word should be added on three subjects, trigonometry (represented by Hipparchus, Menelaus, and Ptolemy), practical mechanics and engineering (Heron), and algebra (Diophantus).

Although the beginnings of trigonometry go back to Aristarchus and Archimedes, Hipparchus, the greatest Greek astronomer, was the first person who can be proved to have used trigonometry systematically. He wrote a treatise in twelve books on *Chords in a Circle,* equivalent to a table of trigonometrical sines. For calculating arcs in astronomy from other arcs given by means of tables

he used propositions in spherical trigonometry. The extant works on the geometry of the sphere by Autolycus of Pitane and Theodosius contain no trigonometry; but the *Sphaerica* of Menelaus (fl. A.D. 100), extant in Arabic only, contains in Book III genuine spherical trigonometry consisting of the so-called Menelaus's Theorem and deductions therefrom.

Hipparchus made his astronomical observations between 161 and 126 B.C. He is famous for having discovered the Precession of the Equinoxes, calculated the mean lunar month at 29 days, 12 hours, 44 minutes, 2½ seconds (which differs from the present accepted figure by less than a second), and compiled a catalogue of some 850 stars; he seems to have been the first to give the position of these stars in terms of latitude and longitude with reference to the ecliptic. His system may be taken to be embodied in Ptolemy's great work, the *Syntaxis*—the name "Almagest" is a corruption of the name given to it by the Arabs—the Ptolemaic system, of course, held the field till the age of Copernicus.

Heron of Alexandria wrote, besides a commentary on Euclid, books dealing with the mensuration of plane and solid figures. How much of those which have come down to us under his name are really Heron's is uncertain; the most authentic is no doubt the *Metrica* in three books only discovered in 1903. He wrote three books on *Mechanics,* only extant in Arabic; this work contains the parallelogram of velocities, the definition of and problems on the center of gravity, an account of the five mechanical powers, and the mechanics of daily life (queries and answers). Other mechanical works of his are on engines of war, the automatic theater, and a book called *Pneumatica* where we find such things as syphons, Heron's Fountain, penny-in-the-slot machines, a fire-engine, a water-organ, and many arrangements employing the force of steam.

We come lastly to algebra. It is curious that we do not find in any Greek author before Heron the arithmetical solution of a quadratic equation as such, though the Babylonians solved such equations in numbers according to a regular rule as early as 2000-1800 B.C.; the Greeks solved them geometrically down to the time

of Heron, and even he used nothing of the nature of algebraical symbols. The first to do this was Diophantus (about 250 A.D.). He had signs for the unknown quantity and its powers up to the sixth, although these signs were little or nothing more than abbreviations of words; he called the unknown quantity ἀριθμός, "number," simply, and its powers δύναμις κύβος (the words for square and cube) etc.; he had also a sign for *minus* indicating λεῖψις, λείψας or λιπών, "leaving" or "wanting," and for "equal." Diophantus's work is called *Arithmetica* and was originally in thirteen books, of which only six survive. In this treatise there are problems leading to simple or quadratic equations; one leads to a very special case of a cubic. Diophantus solves quadratic equations in accordance with a definite formula, like the Babylonians. But the essence of the treatise is that it is devoted to indeterminate or semideterminate analysis, mainly of the second degree, which is known as Diophantine analysis, associated in modern times with the names of Fermat and Euler. Diophantus's problems are extraordinarily varied in kind and his devices for solving them wonderfully ingenious; he requires that the solutions shall be in numbers integral or fractional. This is the sort of thing: "Given a number, to find three others such that the sum of the three, or of any pair of them, together with the given number is a square" or "To find four numbers such that the square of their sum *plus* or *minus* any one of the numbers is a square."

D'Arcy Wentworth Thompson

ON ARISTOTLE AS A BIOLOGIST: WITH A PROOEMION ON HERBERT SPENCER*

Herbert Spencer was born when the last century was young, and this century was in its cradle when he passed away. *Ipse Epicurus obit,* cried the poet of a philosophy which of all the systems of antiquity was most kindred to Spencer's own. A like thought passed through many men's hearts when Herbert Spencer died—men of all nations and languages, for while Spencer lived his voice reached far and wide, even to the ends of the earth. He was a philosopher not speaking to the philosophers, nor teaching in the schools; but he had a gift and a message, so in touch with the temper of his time, that it made him a speaker, *ex cathedra,* to the world. No philosopher of modern times, not Kant himself, has exercised in his lifetime so wide a dominion. Only here and there, among men of a very different stamp, in men like Byron or Rousseau or Tolstoi, do we see that strange power of captivating the imagination of an age, of speaking with a voice that goes out into all lands. The foundation under whose auspices we gather here, the gift of an Indian scholar, reminds us of Spencer's influence in the East: in still more distant

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Japan his counsel was sought when the nation issued from its seclusion to join in the labours and anxieties of the modern world; he stirred the restless blood of Russians and of Poles; in America his books were read far more sedulously than at home; and all this great influence was won without literary art or any charm of magic words, without the fire of Tolstoi, the poetry of Heine or of Byron, the beauty of Rousseau's prose. But Spencer had something in common with all those men, as his popularity was commensurate with their own. And that bond of likeness lay in the fact that to men weary of old trammels and of old burdens he seemed to point, he tried to offer,[1] a way of emancipation, a path of deliverance from creeds outworn. By the world which he addressed he was welcomed and acclaimed, in the spirit in which Heine wished to be remembered, as a gallant soldier, *ein tapfrer Krieger,* in the fight for freedom.

Let us recall, with all brevity, some few circumstances of Spencer's life, that our minds may keep his memory green.

Of that narrow, ascetic, and fiercely independent home of his boyhood we have all read or heard—with its atmosphere of struggle, of criticism, of scientific and political discussion, unrelieved by humour, by letters, or by art. We remember how he went forth as a lad to labour, at an age when men have not yet come up to the University; and how, as an engineer's assistant, he helped to plan bridges and direct gangs of navvies on the great new road to Birmingham and Crewe, and shared in all the fever and haste of that great period of construction. These were the years that he spoke of afterwards as "the futile part of his life"; but it is as plain as an open book that they were years in which his mind was moulded and his mechanical outlook on phenomena developed and confirmed. Again, we remember his years of journalism, during which, after the appearance of his first book, he soon emerged from a lonely life, and with the friendship of George Eliot and Lewes,

[1] Compare the opening passage of *Social Studies* (1864). " 'Give us a guide,' cry men to the philosopher. 'We would escape from these miseries in which we are entangled,' " &c.

Huxley, Tyndall, and many more, found his place in the world of London. Henceforth, his life was so quiet, simple and retired, that we might say of him, as Heine said of Kant, "Er hatte weder Leben noch Geschichte."

In 1855, in the *Principles of Psychology,* Spencer affirmed his belief in the "development hypothesis,"[2] as accounting for the origin of species; and as accounting also for the successive association of ideas, and so, by their becoming "innate" and transmissible from generation to generation, for the gradual development of mind: which latter investigation, I need hardly say, has since been continued, by a long line of evolutionary psychologists, in their several and divergent ways. It is curious to learn from his Autobiography that about this time, in his talks with Huxley, it was the latter who still preserved a guarded attitude, and Spencer who urged upon him, but with still inadequate and unconvincing arguments, the hypothesis of organic evolution.

Five years later, a year after the publication of *The Origin of Species,* Spencer brought out the prospectus of his *Synthetic Philosophy,* that heroic effort to combine, in a Philosophy of Evolution, the whole range of physical, mental, and social science. To discover and trace that one identical phenomenon of evolution, in the progress of civilization, in the development of mind, in the course of nature, in the history of the Universe, was his single and life-long aim.

He found such tools as he worked with in the current tendencies of political and economic thought, and in the recent discoveries or generalizations of science. Of these latter, on the physical side, the greatest was the principle of the Conservation of Energy, the final result of the doctrine of the correlation of the physical forces, in establishing which Rumford had led the way; while on the biological side he drew inspiration from the fact, indicated by Aristotle, developed by Wolff and Milne-Edwards, made into an aphorism by Von Baer, that as the organism grows it grows continually from

[2] As already, in 1852, he had done in his essay on the *Development Hypothesis.*

the simple to the complex, from the homogeneous to a greater and greater heterogeneity.[3]

But many years before Von Baer a greater than he had enunciated the same truth, and had set it forth in even plainer and better words. It was Goethe, in his *Zur Morphologie,*[4] who laid it down as a law that "the more imperfect a being is, the more do its individual parts resemble each other, and the more do these parts resemble the whole. The more perfect the being is, the more dissimilar are its parts. In the former case the parts are more or less a repetition of the whole; in the latter case they are totally unlike the whole. The more the parts resemble each other, the less subordination is there of one to the other; and subordination of parts is the mark of high grade of organization.[5] Now these words are found in the *Life of Goethe,* by Lewes, Herbert Spencer's closest friend. We can scarce avoid the inference that it may have been the poet's insight and the poet's words, quite as much as Von Baer's, that crystallized in his famous formula of evolution. And the inference is confirmed by the fact that, though it was to Von Baer that Spencer was afterwards in the habit of ascribing the law, yet, on the first occasion when he mentions it, he speaks of it as having been established "by the investigations of Wolff, Goethe, and Von Baer." [6]

As in former days Descartes, and as Democritus and Epicurus in days of old, so did Spencer find in matter and in motion, or rather in matter and in force, the fabric of a world. He draws a broad picture, confessedly of a mechanical kind, of alternate cosmic rhythms of the Universe, in which as motion is dissipated, so matter cleaves from the dispersed and homogeneous into more coherent and more segregated shapes; until in the turn of the great

[3] The "law of differentiation," or of "organic progress," was first propounded by Spencer in his essay on *Progress, its Law and Cause* (1857), where he argued that it was also the law of all progress whatsoever.
[4] 1807 (written in 1795). Republished in Goethe's *Werke,* xxxvi, p. 7.
[5] Lewes, *Life of Goethe* (1855), 3rd ed. 1875, p. 358.
[6] Von Baer himself claimed no priority. "Dieses Gesetz ist wohl nie verkannt worden," *Zur Entwicklungsgesch.* (1), p. 153.

wheel, a new redistribution of matter and motion takes place, and evolution is inevitably followed by dissolution at its heels; so the whole present order perishes, *exitio terras cum dabit una dies.* Nevertheless, so vast is the cosmic rhythm, that again the wheel turns, and the dust and ashes of a Universe are co-ordinated and integrated anew, to make "another and another frame of things, for ever!"

All the while Spencer recognizes that Space, Time, Motion, and Matter itself are remote from Absolute Reality, and have their source in our own Empiricism. The "Persistence of Force" is the only truth which transcends experience; and what we ultimately mean by the persistence of force is a cause which transcends our conception and our knowledge.

In his *Biology* Spencer takes for his keynote his conception of life, as having for its chief characteristic a continuous adjustment of the organism to its environment, of its internal to its external relations. So structure follows upon function and functional need, and hereditary transmission hands on to the next generation the advances that the past generation has made: life produces organization, and not organization life. Again, in certain chapters which are by no means the least interesting of the book, he shows,[7] after the fashion of the engineer, and from the experience of the bridge-builder,[8] how the principles of stress and strain are concerned in the fabric, and in the physiology, of the organism; how physical and mechanical relations alter in the organism with increasing bulk;[9] and how incident forces of gravity, growth, and pressure control or determine the shape of leaf and bone and single cell. Under the guidance of a wholesome restraint, a whole school of morpholo-

[7] As in an earlier essay on *The Law of Organic Symmetry,* 1859.

[8] Even in his *Sociology,* where he discusses the place of the *pontifices* in an archaic priesthood, he seems to dally with peculiar affection over these old *bridge-builders.*

[9] A curious corollary, or case in point, is found in the fact that definite limits are set to the size of a terrestrial animal, and still more to that of a flying bird, while the aquatic animal, comparatively immune from gravity, increases in locomotive speed, as a ship does, the bigger it becomes (*Princ. of Biology* (2nd ed.), i. 156).

gists, Roux's school of *Entwickelungsmechanik,* are now investigating these self-same problems, and so bringing to the help of morphology some of those physical concepts which began to be the stock-in-trade of the physiologists when Majendie wrote his *Leçons sur les phénomènes physiques de la Vie* (1830).

In the *Ethics,* Spencer undertakes to establish "rules of right conduct" on a scientific basis, and he does not minimize the difficulty of getting rid of "supernatural ethics," nor of forming a science of "what ought to be." Nevertheless, he does his best to connect absolute Ethics with his universal formula of cosmic evolution and equilibration. Ethics must be based on science, and not on metaphysics. There is, he holds, not only an Ethic for all reasonable beings, but a principle of Ethic for all living things; life and not reason is the essential thing. All conservation implies evolution, and individuality is developed by the inevitable changes of a changing world.[10] So Spencer labours, but perhaps in vain, to make the best of the *bellum omnium contra omnes,* to find in the biological process of adjustment a continual tendency to happiness, and in sociological evolution a tendency to ultimate harmony; in the which a somewhat complacent altruism shall satisfy the egoist, and pleasure will consist in actions which are salutary to the individual and the race. All very much as Mr. Bridges puts it:

For Nature did not idly spend
Pleasure; she ruled it should attend
On every act that doth amend
Our life's condition;
'Tis therefore not well-being's end
But its fruition.

So through all the circle of the sciences, Spencer tried to satisfy that craving inherent in mankind for a constructive system, which shall, in a single unity, frame all the phenomena of the world: for such a unification as in Aristotle's hands had endured unshaken for

10 "C'est là l'idée capitale qu'il ajoute aux doctrines de Zénon, de Spinoza et de Volney": Guyau, *La Morale anglaise contemporaine,* 1885, p. 268.

nigh two thousand years. To bring the world of fact and the world of intelligence into the unity of a system is the task which all philosophers essay, in the light of the knowledge and the spirit of their time; but as knowledge grows, and men's ways and circumstances change, so does philosophy itself, like all else in the world, undergo its own inevitable and endless evolution—giving place, if not to the better, to the new.[11]

But let me not omit to say a word of Spencer's attitude to "the insoluble mystery," of his *confessio ignorantis,* of his share in that Agnosticism for which Huxley found a name. "At the utmost extent of his tether," to borrow words from Locke, "he sat down in quiet ignorance of those things which he found to be beyond the reach of his comprehension."

By a bold abstraction Spencer puts asunder things that our thought insists shall be conjoined. And, through relation, association, and causation, he carried to their bitter end those theories of empiricism, and of the relativity of knowledge, that were no new thing in philosophy, but had percolated down to him through Mansel and through Hamilton, from Locke and Hume and Kant, through all those who had discussed the possibility of knowledge in itself; carried them to their bitter end, and stripped them bare of the garments of the old philosophy, of intuition, or of faith, wherewithal they were wont to be clothed. And in so doing it may seem to many of us that he stopped short but a little way along that steep and narrow road, that *parvus trames,* which is the Pathway from Appearance to Reality.

Ipse Epicurus obît, decurso lumine vitae—"when the lamp of life ran low." And so too Spencer died—as it were but yesterday—full of years and of honour. And to the multitude of friends, disciples, mourners, gathered at his grave, a wise and eloquent man spoke a few noble words. He spoke of Spencer's deep affections and lasting friendships, of the houses that he entered as an habitual guest and honoured friend; of the magnitude of his task, of his un-

[11] The last words are quoted from Alden, *A Study of Death* (1895), 1903, p. 176; cf. *North Amer. Review,* January 1913.

wearied struggle, and of his joy when his work was done; of his "coherent, luminous, conception of the evolution of the world"; of his exaltation of man's individual freedom, of the ethical purpose that underlay his quest of truth. And, lastly, Lord Courtney spoke of Spencer's last brave effort, in the *Riddle of the Universe,* to face and scrutinize the implacable facts of life: of how in the end he had confessed himself overawed by the vastness of the unknowable, appalled by the great vision of Everlasting Law, and silent in the contemplation of the Infinite and the Eternal.

And now that I have tried to pay, in not ungrateful words, our annual tribute to Spencer's memory, as to one who has been a great influence in our world, whose words have become part of our familiar speech, and whose thought has interpenetrated and commingled with our own, let me proceed for what time remains towards another, but I hope a cognate, theme.

In passing from Spencer to Aristotle, we turn from the one philosopher of our own times who has made biology an intrinsic part of his sociology and his psychology, to the great biologist of antiquity, who is *maestro di color che sanno,* in this science as in so many other departments of knowledge. And by the analogy of contrast, we can scarce think of Herbert Spencer's biology without recurring to that of Aristotle, so reverting from a great teacher of mechanical causation to him who taught us our first clear lessons of the phenomena of Life. But, save only by repeating what I have said, that Spencer came to the study of biology in the spirit and with the equipment of the engineer, and by declaring that Aristotle seems to me to have been first and foremost a biologist, by inclination and by training, I will not attempt to pursue the comparison. Let us simply glance at some parts of Aristotle's *Natural History,* and attempt to show, in a partial and elementary way, the influence of that study upon his mind.

The naturalist is born a naturalist, and we may be sure that Aristotle was a lover and a student of nature from a boy; but it would help us to trace the relation of his biological studies to his

philosophical work if we could ascertain when his chief biological work was done. It has often been held that Aristotle devoted himself to biology as an old man's recreation, after his retirement to Euboea. This theory is not adequate, and I do not think it is true. Another legend, that Alexander sent his pupil specimens from his campaigns, Cuvier accepted and Humboldt denied; there is no evidence for it, direct or indirect, in Aristotle's writings, and this tradition also I believe to be worthless. But there is evidence, of a geographical kind, that helps us to answer our preliminary question.

Among the isles of Greece there is a certain island, *insula nobilis et amoena,* which Aristotle knew well. It lies on the Asian side, between the Troad and the Mysian coast, and far into its bosom, by the little town of Pyrrha, runs a broad and sheltered lagoon. It is the island of Lesbos. Here Aristotle came and spent two years of his life, in middle age, bringing his princess-bride from the petty court of a little neighbouring state where he had already spent three years. It was just before he went to Macedon to educate Alexander; it was ten years later that he went back to Athens to begin teaching in the Lyceum. Now in the *Natural History* references to places in Greece proper are very few indeed; there is much more frequent mention of places on the northern and eastern coasts of the Aegean, from Aristotle's own homeland down to the Carian coast; and to places in and round that island of Lesbos, or Mitylene, a whole cluster of Aristotle's statements and descriptions refer. Here, for instance, Aristotle mentions a peculiarity of the deer on a neighbouring islet, of the weasels by the wayside near another island town. He speaks of the big purple Murex shells at Cape Lectum, and of the different sorts of sponges found on the landward and the seaward side of Cape Malia. But it is to the lagoon at Pyrrha that Aristotle oftenest alludes. Here were starfish in such abundance as to be a pest to the fishermen; here the scallops had been exterminated by a period of drought, and by the continual working of the fisherman's dredge; here the sea-urchins come into season in the winter time, an unusual circumstance. Here among

the cuttlefishes was found no octopus, either of the common or of the musky kind; here was no parrot-wrasse, nor any kind of spiny fish, nor sea-crawfish, nor the spotted nor the spiny dog-fish; and, again, from this lagoon, all the fishes, save only a little gudgeon, migrated seaward to breed. And though with no special application to the island, but only to the Asiatic coast in general, I may add that the chameleon, which is the subject of one of Aristotle's most perfect and minute investigations, is here comparatively common, but is not known to occur in Greece at all.

I take it then as probable, or even proven, that an important part of Aristotle's work in natural history was done upon the Asiatic coast, and in and near to Mitylene.[12] He will be a lucky naturalist who shall go some day and spend a quiet summer by that calm lagoon, find there all the natural wealth ὅσσον Λέσβος . . . ἐντὸς ἐέργει, and have around his feet the creatures that Aristotle loved and knew. Moreover, it follows for certain, if all this be true, that Aristotle's biological studies preceded his more strictly philosophical work; and it is of no small importance that we should be (as far as possible) assured of this, when we speculate upon the influence of his biology on his philosophy.[13]

Aristotle is no tyro in biology. When he writes upon Mechanics or on Physics we read him with difficulty: his ways are not our ways; his explanations seem laboured; his science has an archaic look, as it were coming from another world to ours, a world before Galileo. Speaking with all diffidence, I have my doubts as to his mathematics. In spite of a certain formidable passage in the Ethics, where we have a sort of *ethica more geometrico demonstrata,* in

[12] Perhaps it was here also that Aristotle found his "Lesbian rule."

[13] Pursuing my geographical inquiries a very little further, I have discovered that of the very large number of place-names mentioned in the *Problems,* by far the greater number are situated in Southern Italy, that is to say in Magna Graecia, or in Sicily; and I live in hopes of seeing this work, or a very large portion of it, expunged, for this and other weightier reasons, from the canonical writings of Aristotle. In the treatise *De Plantis,* which is already acknowledged to be spurious, only three or four geographical names, I think, occur; but they likewise are every one of them situated within the bounds of Magna Graecia.

spite of his favourite use of the equality of the angles of a triangle to two right angles as an example of proof indisputable, in spite even of his treatise *De Lineis Insecabilibus,* I am tempted to suspect that he sometimes passed shyly beneath the superscription over Plato's door.

But he was, and is, a very great naturalist. When he treats of Natural History, his language is our language, and his methods and his problems are well-nigh identical with our own. He had familiar knowledge of a thousand varied forms of life, of bird and beast, and plant and creeping thing. He was careful to note their least details of outward structure, and curious to probe by dissection into their parts within. He studied the metamorphoses of gnat and butterfly, and opened the bird's egg to find the mystery of incipient life in the embryo chick. He recognized great problems of biology that are still ours today, problems of heredity, of sex, of nutrition and growth, of adaptation, of the struggle for existence, of the orderly sequence of Nature's plan. Above all he was a student of Life itself. If he was a learned anatomist, a great student of the dead, still more was he a lover of the living. Evermore his world is in movement. The seed is growing, the heart beating, the frame breathing. The ways and habits of living things must be known: how they work and play, love and hate, feed and procreate, rear and tend their young; whether they dwell solitary, or in more and more organized companies and societies. All such things appeal to his imagination and his diligence. Even his anatomy becomes at once an *anatomia animata,* as Haller, poet and physiologist, described the science to which he gave the name of *physiology.* This attitude towards life, and the knowledge got thereby, afterwards helped to shape and mould Aristotle's philosophy.

I have no reason to suppose that the study of biology "maketh a man wise," but I am sure it helped to lead Aristotle on the road to wisdom. Nevertheless he takes occasion to explain, or to excuse, his devotion to this study, alien, seemingly, to the pursuit of philosophy. "Doubtless," he says,[14] "the glory of the heavenly bodies fills

[14] *De Part. Anim.* i. 5.

us with more delight than we get from the contemplation of these lowly things; for the sun and stars are born not, neither do they decay, but are eternal and divine. But the heavens are high and afar off, and of celestial things the knowledge that our senses give us is scanty and dim. On the other hand, the living creatures are nigh at hand, and of each and all of them we may gain ample and certain knowledge if we so desire. If a statue please us, shall not the living fill us with delight; all the more if in the spirit of philosophy we search for causes and recognize the evidences of design. Then will Nature's purpose and her deep-seated laws be everywhere revealed, all tending in her multitudinous work to one form or another of the Beautiful." In somewhat similar words does Bacon[15] retranslate a familiar saying: "He hath made all things beautiful according to their seasons; also he hath submitted the world to man's inquiry." On the other hand, a most distinguished philosopher of today is struck, and apparently perplexed, by "the awkward and grotesque, even the ludicrous and hideous forms of some plants and animals." [16] I commend him, with all respect, to Aristotle—or to that Aristotelian verity given us in a nutshell by Rodin, "Il n'y a pas de laideur!"

To be sure, Aristotle's notion of beauty was not Rodin's. He had a philosopher's comprehension of the Beautiful, as he had a great critic's knowledge and understanding of Poetry; but wise and learned as he was, he was neither artist nor poet. His style seldom rises, and only in a few such passages as that which I have quoted, above its level didactic plane. Plato saw philosophy, astronomy, even mathematics, as in a vision; but Aristotle does not know this consummation of a dream. The bees have a king, with Aristotle. Had Plato told us of the kingdom of the bees, I think we should have had Shakespearian imagery. The king would have had his "officers of sorts," his magistrates, and soldiers, his "singing masons building roofs of gold." Even Pliny, arid encyclopaedist as he is, can now and then throb and thrill us as Aristotle cannot do—for ex-

[15] *De Sapientia Veterum* (Eccles. iii. 11).
[16] Ward, op. cit., p. 85.

ample, when he throws no little poetry and still more of music into his description of the nightingale's song.[17]

But let us now come, at last, to exemplify, by a few brief citations, the nature and extent of Aristotle's zoological knowledge. And here, brevity bids me choose between two ways: either to deal with Aristotle's theories or his facts, his insight or his erudition. The former are of the highest possible interest to us, and their treatment partly includes the latter. But it would take more than all the time I have, to deal with any one of Aristotle's theories—of generation, for instance, or of respiration and vital heat, or those still weightier themes of variation and heredity, the central problems of biology, or again the teleological questions of adaptation and design.

Let me therefore confine myself, almost wholly, to a few fragments out of his storehouse of zoological and embryological facts.

Among the bloodless animals, as Aristotle called what we call the Invertebrates, he distinguishes four great genera, and of these the Molluscs are one. These are the cuttle-fish, which have now surrendered their Aristotelian name of "molluscs" to that greater group, which is seen to include them with the shell-fish, or "ostracoderma" of Aristotle. These cuttle-fishes are creatures that we seldom see, but in the Mediterranean they are an article of food, and many kinds are known to the fishermen. All, or well-nigh all, of these common kinds were known to Aristotle, and his account of them has come down to us with singular completeness. He describes their form and their anatomy, their habits, their development, all with such faithful accuracy that what we can add today seems of secondary importance. He begins with a methodical description of the general form, tells us of the body and fins, of the eight arms with their rows of suckers, of the abnormal position of the head. He points out the two long arms of Sepia and of the Calamaries, and their absence in the octopus; and he tells us, what was only confirmed of late, that with these two long arms the creature clings to the rock and sways about like a ship at anchor. He describes the great eyes, the two big teeth forming the beak; and he dissects the

[17] *H. N.* x. 43 (29).

whole structure of the gut, with its long gullet, its round crop, its stomach and the little coiled caecal diverticulum; dissecting not only one but several species, and noting differences that were not observed again till Cuvier re-dissected them. He describes the funnel and its relation to the mantle-sac, and the ink-bag, which he shows to be largest in Sepia of all others. And here, by the way, he seems to make one of those apparent errors that, as it happens, turn out to be justified: for he tells us that in Octopus the funnel is on the upper side; the fact being that when the creature lies prone upon the ground, with all its arms spread and flattened out, the funnel-tube (instead of being flattened out beneath the creature's prostrate body) is long enough to protrude upwards between arms and head, and to appear on one side or other thereof, in a position apparently the reverse of its natural one. He describes the character of the cuttle-bone in Sepia, and of the horny pen which takes its place in the various Calamaries, and notes the lack of any similar structure in Octopus. He dissects in both sexes the reproductive organs, noting without exception all their essential and complicated parts; and he had figured these in his lost volume of anatomical diagrams. He describes the various kinds of eggs, and, with still more surprising knowledge, shows us the little embryo cuttle-fish, with its great yolk-sac, attached (in apparent contrast to the chick's) to the little creature's developing head.

But there is one other remarkable structure that he knew, centuries before it was rediscovered almost in our own time. In certain male cuttle-fishes, in the breeding season, one of the arms develops in a curious fashion into a long coiled whip-lash, and in the act of breeding may then be transferred to the mantle-cavity of the female. Cuvier himself knew nothing of the nature or the function of this separated arm, and indeed, if I am not mistaken, it was he who mistook it for a parasitic worm. But Aristotle tells us of its use and its temporary development, and of its structure in detail, and his description tallies closely with the accounts of the most recent writers.

Among the rarer species of the group he knew well the little

Argonaut, with its beautiful cockle-shell, and tells how it puts up its two broad arms to sail with, a story that has been rejected by many, but that after all may perhaps be true.

Now in all this there is far more than a mass of fragmentary information gleaned from the fishermen. It is a plain orderly treatise, on the ways and habits, the varieties, and the anatomical structure of an entire group. Till Cuvier wrote there was none so good, and Cuvier lacked knowledge that Aristotle possessed.

Not less exact and scarcely less copious is the chapter in which Aristotle deals with the crab and lobster, and all such crustacean shell-fish, nor that in which he treats of insects, after their kind. Most wonderful of all, perhaps, are those portions of his books in which he speaks of fishes, their diversities, their structure, their wanderings, and their food. Here we may read of fishes that have only recently been rediscovered,[18] of structures only lately reinvestigated, of habits only of late made known.[19] And many such anticipations of our knowledge, and many allusions to things of which we are perhaps still ignorant, may yet be brought to light; for we are still far from having interpreted and elucidated the whole mass of Aristotle's recorded erudition: which whole recorded mass is only, after all, *tanquam tabula naufragii.*

There is perhaps no chapter in the *Historia Animalium* more attractive to the anatomist than one which deals with the anatomy and mode of reproduction of the cartilaginous fishes, the sharks and rays, a chapter which moved to admiration that prince of anatomists Johannes Müller.[20] The latter wrote a volume on the text of a page of Aristotle, a page packed full of a multitude of facts, in no one of which did Johannes Müller discover a flaw. The subject is technical, but the gist of the matter is this: that among these Selachians (as,

[18] E.g. *Parasilurus Aristotelis,* a siluroid fish of the Achelous.

[19] E.g. the reproduction of the pipe-fishes (Syngnathi), the hermaphrodite nature of the Serrani, the nest-building of the Wrasses, &c., &c.

[20] Cf. Cavolini, in his classical *Mem. sulla Generazione dei Pesci,* Naples, 1787: "E quando io . . . scorro la Storia degli Animali di Aristotile, non posso non essere da stupore preso, in esse leggendo veduti quei fatti, che a noi non si son potuti che a stento manifestare: e rilevati poi con tutta la nettezza, e posti in parallelo coi fatti gia riconosciuti nel feto del gallo; &c."

after Aristotle, we still sometimes call them) there are many diversities in the structure of the parts in question, and several distinct modes in which the young are brought forth or matured. For in many kinds an egg is laid, which eggs, by the way, Aristotle describes with great minuteness. Other kinds do not lay eggs, but bring forth their young alive, and these include the Torpedo and numerous sharks or dogfish. The eggshell is in these cases very thin, and breaks before the birth of the young. But among them there are a couple of sharks, of which one species was within Aristotle's reach, where a very curious thing happens. Through the delicate membrane, which is all that is left of the eggshell, the great yolk-sac of the embryo becomes connected with the parental tissues, which infold and interweave with it; and by means of this temporary union the blood of the parent becomes the medium of nourishment for the young. And the whole arrangement is physiologically identical with what obtains in the higher animals, the mammals, or warm-blooded vivipara. It is true that the yolk-sac is not identical with that other embryonic membrane which comes in the mammals to discharge the function of which I speak; but Aristotle was aware of the difference, and distinguishes the two membranes with truth and accuracy.

It happens that of the particular genus of sharks to which this one belongs, there are two species differing by almost imperceptible characters; but it is in one only of the two, the γαλεὸς λεῖος of Aristotle, that this singular phenomenon of the *placenta vitellina* is found. It is found in the great blue shark of the Atlantic and the Mediterranean; but this creature grows to a very large size before it breeds, and such great specimens are not likely to have come under Aristotle's hands. Cuvier detected the phenomenon in the blue shark, but paid little attention to it, and, for all his knowledge of Aristotle, did not perceive that he was dealing with an important fact which the Philosopher had studied and explained. In the seventeenth century, the anatomist Steno actually rediscovered the phenomenon, in the γαλεὸς λεῖος, the *Mustelus laevis* itself, but he was unacquainted with Aristotle. And the very fact was again forgotten until Johannes Müller brought it to light, and showed not

only how complete was Aristotle's account, but how wide must have been his survey of this class of fishes to enable him to record this peculiarity in its relation to their many differences of structure and reproductive habit. I used to think of this phenomenon as one that Aristotle might have learned from the fishermen, but, after a more careful study of Johannes Müller's book, I am convinced that this is not the case. It was a discovery that could only have been made by a skilled and learned anatomist.

In a lengthy and beautiful account Aristotle describes the development of the chick. It is on the third day that the embryo becomes sufficiently formed for the modern student to begin its study, and it was after just three days (a little earlier, as Aristotle notes, in little birds, a little later in larger ones) that Aristotle saw the first clear indication of the embryo. Like a speck of blood, he saw the heart beating, and its two umbilical blood-vessels breaking out over the yolk. A little later he saw the whole form of the body, noting the disproportionate size of head and eyes, and found the two sets of blood-vessels leading, the one to the yolk-sac, the other to the new-formed allantois. In the tiny chick of the tenth day, he saw the stomach and other viscera; he noted the altered position of the heart and great blood-vessels; he traced clearly and fully the surrounding membranes; he opened the little eye to seek, but failed to find, the lens. And at length he describes in detail the appearance and attitude of the little chick, the absorption of the yolk, the shrivelling of the membranes, just at the time when the little bird begins to chip the shell, and before it steps out into the world. While this epitome contains but a part of what Aristotle saw (and without a lens it would be hard to see more than he), it includes the notable fact of the early appearance of the heart, the *punctum saliens* of later writers, whose precedence of all other organs was a chief reason for Aristotle's attributing to it a common, central, or primary sense, and so locating in it the central seat of the soul. And so it was held to be till Harvey's time, who, noting the contemporaneous appearance of heart and blood, held that the contained was nobler than that which contained it, and that it was

the blood that was "the fountain of life, the first to live, the last to die, the primary seat of the soul, the element in which, as in a fountain-head, the heat first and most abounds and flourishes"; so harking back to a physiology more ancient than Aristotle's—"for the blood is the life thereof." All students of the *Timaeus* know that here Aristotle parted company with Plato, who, following Hippocrates, and Democritus, and others, placed the seat of sensation, the sovereign part of the soul, in the brain. Right or wrong, it was on observation, and on his rarer use of experiment,[21] that Aristotle relied. The wasp or the centipede still lives, when either head or tail is amputated, the tortoise's heart beats when removed from the body, and the heart is the centre from which the blood vessels spring. To these arguments Aristotle added the more idealistic belief that the seat of the soul, the ruling force of the body, must appropriately lie in the centre: and he found further confirmation of this view from a study of the embryo plant, where in the centre, between the seed-leaves, is the point from which stem and root grow. And Ogle reminds us how, until a hundred years ago, botanists still retained an affectionate and superstitious regard for that portion of the plant, calling it now *cor,* now *cerebrum,* the plant's heart or brain.

And now is it possible to trace directly the influence of Aristotle's scientific training and biological learning upon his sociology, his psychology, or in general on his philosophy? That such an influence must have been at work is, prima facie, obvious. The physician who becomes a philosopher will remain a physician to the end; the engineer will remain an engineer; and the ideas of pure mathematics, Roger Bacon's "alphabet of philosophy," will find issue and expression in the philosophy of such mathematicians as Plato, Leibnitz, Spinoza, or Descartes. Moreover, it is not only the special training or prior avocation of the philosopher that so affects his mind. In divers historical periods the rapid progress or the diffused study of

21 Aristotle's experiments were akin to Voltaire's, who employed himself in his garden at Ferney in cutting off the horns and heads of snails, to see whether, or how far, they grew again.

a particular science has moulded the philosophy of the time. So on a great scale in the present day does biology; so did an earlier phase of evolutionary biology affect Hegel; and in like manner, in the great days after Lavoisier, the days of Dalton, Davy and Berzelius, did chemistry help, according to John Stuart Mill, to suggest a "chemistry of the mind" to the "association" psychologists. A certain philosopher,[22] in dealing with this theme, begins by telling us that "Mathematics was the only science that had outgrown its merest infancy among the Greeks." Now it is my particular purpose today to show, from Aristotle, that this is not the case. Whether Aristotle's biological forerunners were many or few, whether or not the Hippocratics (for instance) had failed to raise physiology and anatomy to the dignity of a science, or having done so, had only reserved them, as a secret cult, to their own guild; in short, whether Aristotle's knowledge is in the main the outcome of his solitary labours, or whether, as Leibnitz said of Descartes, *praeclare in rem suam vertit aliorum cogitata,* it is at least certain that biology was in *his* hands a true and comprehensive science, only second to the mathematics of his age.

The influence, then, of scientific study, and in particular of Biology, is not far to seek in Aristotle's case. It has ever since been a commonplace to compare the state, the body politic, with an organism, but it was Aristotle who first employed the metaphor. Again, in his exhaustive accumulation and treatment of political facts, his method is that of the observer, of the scientific student, and is in the main inductive. Just as, in order to understand fishes, he gathered all kinds together, recording their forms, their structure, and their habits, so he did with the Constitutions of cities and of states. Those two hundred and more πολιτεῖαι which Aristotle laboriously compiled, after a method of which Plato would never have dreamed, were to form a Natural History of Constitutions and Governments. And if we see in his concrete, objective treatment of the theme a kinship with Spencer's Descriptive Sociology, again;

[22] Ritchie, *Darwin and Hegel,* p. 39.

I think, a difference is soon apparent, between Spencer's colder catalogue of facts and Aristotle's more loving insight into the doings and into the hearts, into the motives and the ambitions, of men.

But whatever else Aristotle is, he is the great Vitalist, the student of the Body with the Life thereof, the historian of the Soul.

Now we have already seen how and where Aristotle fixed the soul's seat and local habitation. But the soul has furthermore to be studied according to its attributes, or analysed into its "parts." Its attributes can be variously analysed, as in his *Ethics* Aristotle shows. But it is in the light of Biology alone that what amounts to a scientific analysis, such as is developed in the *De Anima,* becomes possible; and in that treatise it is only after a long preliminary physiological discussion that Aristotle at length formulates his distinctive psychology. There is a principle of continuity, a συνέχεια, that runs through the scale of structure in living things, and so, little by little, by imperceptible steps, does Nature make the passage from plant, through animal, to man. It is with all the knowledge, summarized in a great passage of the *Natural History,* and embodied in this broad generalization, that Aristotle afterwards proceeds to indicate the same gradation in psychology, and to draw from it a kindred classification of the Soul.

There is a soul which presides over the primary physiological requirement of nutrition, a soul already inherent in the plant and inseparable from life itself; it is ἡ πρώτη ψυχή. Common likewise to all living things are the physiological functions of growth and reproduction, and the psychical agencies directing these are concomitant with, and in fact identical with, the nutrient soul. Sensation or sensibility, whereby the animal essentially differs from the plant, distinguishes the αἰσθητική ψυχή, the sentient soul; and the soul of movement, undisplayed in the very lowest of animals, presently accompanies the soul of sensibility. At length the reasoning soul, the διανοητική ψυχή, or νοῦς, emerges in man, as the source of his knowledge and his wisdom.[23] In a brief but very important

[23] I have here borrowed some words from a former address, and from my notes on the *Historia Animalium.*

passage,[24] with a touch of that Platonic idealism never utterly forgotten by him (and so apt to bring Wordsworth to our own minds), Aristotle tells us that this soul "cometh from afar"—*μόνον θύραθεν ἐπεισιέναι, καὶ θεῖον εἶναι μόνον*. Yes, in very plain Greek prose, this is no less than to assert that "trailing clouds of glory," "it cometh from afar."

But however glorified be the reasoning soul, yet these parts, these subdivisions of the soul, do not stand apart in mutual exclusiveness, but just as we may discern a triangle within a square, so is each lower grade of *ψυχή* implicit in the higher. And as the higher organisms retain the main physiological faculties of the lower, so do they retain such psychological qualities as these possess: and gradually (more and more as we ascend the ladder) do we find adumbrations of the psychical qualities that will be perfected in the higher forms. Among the higher animals, at least, a comparative psychology may be developed; for just as their bodily organs are akin to one another's and to man's, so also have we in animals an inchoate intelligence, wherein we may study, in one or another, the psychology of such things as fear, anger, courage, and at length of something which we may call sagacity, which stands not far from reason. And, last of all, we have a psychology of childhood, wherein we study in the child, at first little different from the animal, the growing seeds of the mind of man.

But observe before we leave this subject that, though Aristotle follows the comparative method, and ends by tracing in the lower forms the phenomena incipient in the higher, he does not adopt the method so familiar to us all, and on which Spencer insisted, of first dealing with the lowest, and of studying in successive chronological order the succession of higher forms. The historical method, the realistic method of the nineteenth century, the method to which we so insistently cling, is not the only one. Indeed, even in modern biology, if we compare (for instance) the embryology of today with that of thirty years ago, we shall see that the pure historical

[24] *De Gen. An.* ii. 3, 736 b 27. Cf. Brentano, *Aristoteles' Lehre vom Ursprung des menschlichen Geistes,* 1911, p. 18.

method is relaxing something of its fascination and its hold. Rather has Aristotle continually in mind the highest of organisms, in the light of whose integral and constituent phenomena must the less perfect be understood. So was it with one whom the Lord Chancellor of England has called "the greatest master of abstract thought since Aristotle died." For Hegel,[25] as surely for Aristotle also, *Entwicklung* was not a "time-process but a thought-process." To Hegel, an actual, realistic, outward, historical evolution seemed but a clumsy and materialistic philosophy of nature. In a sense, the "time-difference has no interest for thought." And if the lower animals help us to understand ourselves, it is in a light reflected from the study of Man.

So grows up, upon a broad basis of Natural History, the whole psychology of Aristotle, and in particular that great doctrine of the tripartite soul, according to which created things "by gradual change sublimed, To vital spirits aspire, to animal, To intellectual!"

In this ψυχή of Aristotle there was (in spite of the passage which I have quoted) a trace of the concrete and the all but material, which later Greek as well as Christian thought was not slow to discern and to modify. But, as a philosopher of our own day reminds us, it was in relation to a somewhat idealized Body that Aristotle described that somewhat unspiritual Soul. Such as it is, it has remained at the roots of our psychology, even to this day.

Bergson only partially gets rid of it when he recasts Aristotelian psychology on the lines of that branching tree which modern evolutionary biology substitutes for the *scala Naturae* of Aristotle; and when he sees, for instance, in psychological evolution, not the successive grades of continuous development, through sensibility and instinct to intelligence, but rather the splitting up of an original activity, of which instinct and intelligence are not successive, but separate and diverging, outgrowths.

In our recent science the Aristotelian doctrine is not dead. For but little changed, though dressed in new garments, this Aristotelian

25 Ritchie, op. cit. Cf. Höffding, in *Darwin and Modern Science.* Cambridge, 1909, p. 449.

entelechy,[26] which so fascinated Leibnitz,[27] enters into the Vitalism of Hans Driesch; and of those who believe with him, that far as physical laws may carry us, they do not take us to the end: that the limitations of induction forbid us to pass in thought and argument from chemistry to consciousness, or (as Spencer well knew) from Matter to Mind;[28] that Life is not merely "an outstanding difficulty, but a veritable exception to the universal applicability of mechanical laws"; that not to be comprehended under the category of physical cause, but to be reckoned with apart, is the fundamental conception underlying Life and its Teleology.[29]

It is easy so to sketch in simple words the influence of Aristotle's biological studies upon his method of work, or to see in his Psychology and his Ethics the results of his biological analysis of the soul. But his natural science seems to send a still deeper influence running through the whole of his philosophy, for better or for worse, which influence I lack the needful learning to fathom and to describe. I can only see dimly, and cannot venture to explain, how his lifelong study of living things led to his rejection of Plato's idealistic ontology, and affected his whole method of classification, his notion of essentials and accidents, his idea of "Nature" that "makes nothing in vain," his whole analysis of causation, his belief in, and his definition[30] of, Necessity, his faith in design, his particular form of teleology, his conception and apprehension of God.

26 ψυχή ἐστιν ἐντελέχεια ἡ πρώτη σώματος φυσικοῦ δυνάμει ζωὴν ἔχοντος.

27 Cf. Jacoby, *De Leibnitii studiis Aristotelicis*, Berlin, 1867.

28 Cf. Spencer, *Princ. of Psychology* (para. 63): "Though of the two it seems easier to translate so-called Matter into so-called Spirit, than to translate so-called Spirit into so-called Matter (which latter is indeed wholly impossible); yet no translation can carry us beyond our symbols. Such vague conceptions as loom before us are illusions conjured up by the wrong connotations of our words."

29 Cf. Kant's views in the *Kritik der Urteilskraft* and elsewhere, on the teleological aspect of living organisms, with (for instance) Schleiden in the Preface to his *Grundzüge der Botanik* (1860): ". . . durch die Darwinsche Lehre die Teleologie aus der Naturwissenschaft vollständig heraus, und in die erbauliche oder poetische Rede, wo sie hingehört, verwiesen wurde!" Cf. also Professor Sidgwick's remarks on Spencer's "avoidance of teleological explanation," in the *Ethics of T. H. Green*, &c., p. 141.

30 τὸ μὴ ἐνδεχόμενον ἄλλως ἔχειν.

And now, to close my story. It is in no derogation of Spencer's commemorative honour that I have spoken of him together with a greater Philosopher, and one of the greatest of men. So I have used my hour of Oxford to speak, and to salute, the name of Aristotle, here where his spirit has dwelt for six hundred years—I who have humbly loved him since my day began.

We know that the history of biology harks back to Aristotle by a road that is straight and clear, but that beyond him the road is broken and the lights are dim. And we have seen that biology was no mere by-play of Aristotle's learned leisure, but was a large intrinsic part of the vast equipment of his mind.

This our science is no petty handicraft, no narrow discipline. It was great, and big, in Aristotle's hands, and it is grown gigantic since his day.

It begins in admiration of Nature's handiwork, as she strews it by the way. It bids us seek through the land, and search the deep places of the sea. It toils for the health and wealth of men. It speaks of things humble; it whispers of things high. It tells (if I dare use the old theologian's word [31]) of Laws, "whose Voice is the harmony of the World, and whose Seat is the bosom of God."

Sometimes, as today, it brings us by a by-way to the study of the history of human thought and knowledge, and introduces us to a company of great men, dwellers in the "clear air" of Athens.

The little Greek I know, first learnt at my Father's knee, is but a child's plaything to that of many a scholar here. But I hear, now and then, a welcome given, in old Hellenic speech, to men who call at that Interpreter's House wherein Plato and Aristotle show us "excellent things, such as will be a help to us in our journey."

[31] Hooker.

F. Sherwood Taylor

THE ORIGINS OF GREEK ALCHEMY*

DEFINITION OF ALCHEMY

Alchemy is not easily defined. Some would narrow its meaning to "the Transmutation of Metals"; others would include within its range all that pertains to the notions of exaltation and regeneration, whether of metals or of the human mind. Alchemy is identical neither with mysticism nor with metallurgy. One of the earliest alchemical texts, the Φυσικὰ καὶ Μυστικά of Demokritos (*c.* A.D. 100), succinctly expresses by its title the nature of the Art it describes—which may be defined as:—*An art, purporting to relate to the transmutation of metals, and described in a terminology at once Physical and Mystical.*

An inquiry into the origins of Alchemy may proceed by two methods. The safer and more certain is to seek in the earliest texts for evidence, direct or indirect, of their sources: the more ambitious is to extract from these texts—no easy task—their essential ideas, as of transmutation, regeneration, symbolic representation; and to seek to trace these ideas in the philosophies and cults contemporary with or preceding the earliest of alchemical texts. The former and lighter task is here essayed.

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SOURCES OF THE EARLIEST ALCHEMICAL TEXTS

Alchemical texts have been written in every century from the second century B.C. to the nineteenth century A.D.; they hail from every country in Europe and the Near East, from Persia, India, China, and Tibet. But when we seek the origin of the alchemical tradition, we can find direct evidence of the existence of Alchemy before, say, A.D. 300 only in two cultural centres—China and Hellenistic Egypt. Of the early Chinese texts but little is at present known: the texts hailing from Hellenistic Egypt[1] are both voluminous and of great interest. It is with these texts that this article will be chiefly concerned.

POSSIBLE ASSYRIAN SOURCE OF ALCHEMY

In 1925 Robert Eisler drew attention to a remarkable passage contained in an Assyrian clay tablet of the eighth century B.C. The text in question is concerned with the manufacture of glazes, enamels, and precious stones, and appears to allude to the silvering of bronze vessels; its content therefore is distantly related to the subject of Alchemy. The hall-mark of Alchemy is the combination of a spiritual and practical aspect in the making of precious materials; it was therefore of great interest to find that in Assyria magical practices were associated with the setting up of a furnace for such purposes. Here is a translation[2] of the text:

> When thou settest out the (ground) plan of a furnace for "minerals," thou shalt seek out a favourable day in a fortunate month and thou

[1] Prof. T. L. Davis advances the view (*Scientific Monthly*, 1936, xliii, 551-558) that the texts are not strictly alchemical, in that the operations they describe are directed to a staining or colouring of metal, not to a supposed transmutation. With this view I disagree, and hope to express my views in a subsequent number of *Ambix*.

[2] Campbell Thompson, *Chemistry of the Ancient Assyrians*, Luzac, 1925.

shalt set out the (ground) plan of the furnace. While they are making the furnace, thou shalt watch (them) and shalt work thyself (?) (in the house of the furnace): thou shalt bring in embryos[3] (born before their time) another (?), a stranger shall not enter, nor shall one that is unclean tread before them: thou shalt offer the due libations before them: the day when thou puttest down the "mineral" into the furnace thou shalt make a sacrifice before the embryos: thou shalt set a censer of pure incense, shalt pour *kurunnu*-beer before them.

Thou shalt kindle a fire underneath the furnace and shalt put down the "mineral" into the furnace. The men whom thou shalt bring to be over the furnace shall cleanse themselves and (then) *thou shalt set them to be over the furnace or "crude minerals."*

The wood which thou shalt burn under the furnace shall be styrax, thick decorticated billets which have not lain exposed in bundles, (but) have been kept in leather coverings, cut in the month of Ab. This wood shall go underneath thy furnace.

This text antedates Western Alchemy by some eight centuries, and there seems to be a consensus of opinion against regarding it as connected with true Alchemy, on the ground that the association of religious or magical rites with the initiation of a new enterprise, in this case the building of a furnace, is in no way exceptional or necessarily dependent on the purpose to which the furnace was to to be put.

EARLY CHINESE ALCHEMY

The Chinese alchemical texts which have been translated amount only to a few dozen pages: it is difficult therefore for one who is not a sinologue to give any adequate account of them.

The central purpose, at least of practical Chinese Alchemy, seems to have been the prolongation of life by artificially prepared gold—believed to be of greater efficacy than common gold. Chinese Alchemy is connected with Tao-ism, the philosophy of Lao-tzu,

[3] Or crude minerals.

who lived some four centuries before the earliest mention of Alchemy. Essential to his doctrine is the idea of the whole universe being informed by Tao, which may be thought of as analogous to the influence of destiny, the εἱμαρμένη of the Greeks. The doctrine of Tao led to a mystical system whereby the individual could merge himself in Tao and so be freed from the bonds of space and time. This doctrine, like that of every philosophy or religion, was modified by smaller minds to suit their beliefs and desires, chief among which, as always, was the desire for long life. Many were unwilling to undergo the mental and physical discipline of the mystic's life in order to free themselves from the bondage of destiny: these preferred to believe that a medicine could confer the principle of longevity. It was a doctrine associated with Taoism that all things were composed of two principles—*Yin,* the negative principle of femaleness, cold, darkness, death, and matter, and *Yang,* the positive principle of maleness, heat, light, life, and soul. Certain substances, vermilion (cinnabar), gold, silver, and jade, were believed to be particularly rich in *Yang*. Gold, it was believed, could be alchemically prepared from vermilion, and such gold was naturally supposed to have a peculiar power of prolonging life.

This is the central notion of Chinese practical Alchemy, but is totally absent from the Western Alchemy of the first millennium A.D.

The earliest[4] notice of Alchemy in Chinese Literature is contained in the *History* of Ssuma Ch'ien, which appears to be a later addition to the *Treatise on the Sacrifices of Feng and Shan.* The following passage from the *Han Shu XXV* has been translated by Waley, and in the opinion of the latter dates from the first century A.D.:

(The wizard Li) Shao-chun said to the Emperor (Wu Ti of Han): "Sacrifice to the stove (tsao) and you will be able to summon

[4] Prof. William H. Barnes has drawn attention to a doubtful earlier reference in the writings of Chuang Tzu (fourth to third century B.C.). ("Possible references to Chinese Alchemy in the fourth and third century B.C.," W. H. Barnes, *China Journal,* XXIII, 2, p. 75.)

'things' (*i.e.* spirits). Summon spirits and you will be able to change cinnabar powder into yellow gold. With this yellow gold you make vessels to eat and to drink out of. You will then increase your span of life."

As the Emperor Wu Ti lived from 140-86 B.C. and it is unlikely that the incident related was the beginning of Chinese Alchemy, we must suppose that the latter was in existence at least as early as 200 B.C., and may therefore antedate our earliest Greek alchemical writings by some two centuries.

A considerable work on Alchemy, the *Ts'ang T'ung Ch'i*—attributed to Wei Po-yang, perhaps pseudonymously—belongs to the second century. Many later works exist. The tendencies of later Chinese Alchemy are hardly relevant to our study of origins. Suffice it to say that, as in the West, it divided into a practical gold-making craft and a mystical religion in which mental transmutations were operated upon the souls of metals which were mystically equated to various organs of the body.

There seems little reason to believe that the Alchemy of Hellenistic Egypt had any contact with that of China. There is some slight likeness of materials: but to the early Alchemy of the West are unknown the two central notions of Chinese Alchemy, namely, the prolongation of life and the Philosopher's Stone, a minute portion of which would transmute a large quantity of base metal. Both these notions appear in the West for the first time in the alchemical texts of the Arabs.

THE GREEK ALCHEMICAL TEXTS

The authors of the Greek alchemical texts attribute the source of their art to Ancient Egypt. The force of this evidence is much weakened by the tendency of the classical world to attribute all wisdom to the priests of Egypt. The alchemist, moreover, who could believe that the prophet Moses was the author of a very practical set of alchemical recipes does not command our con-

fidence when he speaks of the origin of his art. There is, however, no small amount of internal evidence for an Egyptian source. No direct written evidence of the existence of the Alchemy as defined at the beginning of this article is to be found in the records of ancient Egypt, of ancient Persia, of the Hittites or of classical Greece and Rome, nor do the records of Babylon and Assyria reveal anything concerning Alchemy except the doubtfully alchemical text which has already been discussed.

The quest of the making of gold appears full-fledged in Egypt at a date which cannot be far from A.D. 100. Our sources of knowledge concerning it are derived from papyri and manuscripts. The earliest alchemical document is a fragment of papyrus so far mutilated that we can only tell that it is concerned with the making of silver: its date is about A.D. 70. Of far more interest are two papyri, written at a date not far from A.D. 300 and now in the libraries of Leyden and Stockholm. Whether these papyri are truly alchemical will be a matter for discussion. Suffice it to say that they deal with recipes for artificially preparing gold, silver, asemos (a white silver-like metal), precious stones, and purple; and that, although they contain nothing that is mystical, they make allusion to the alchemist Demokritos, an allusion which indicates that their authors were acquainted with true Alchemy.

The works of the Greek alchemists proper are to be found in very numerous manuscripts, distributed through the libraries of Europe. If we exclude the works written after A.D. 1000, which generally appear in manuscripts separate from those containing the works of the more ancient authors, it may be said that all these manuscripts derive from two originals:

1. The manuscript Marcianus 299 of Venice, copied in the tenth or eleventh century.
2. The manuscripts Parisinus Græcus 2325 of the thirteenth century and 2327 of the fifteenth century, which latter seems to be a more complete copy of the original from which the former, Parisinus Græcus 2325, was taken.

It would appear that a collection of alchemical manuscripts was made in Byzantium in the seventh or eighth century which, after some losses and mutilations, appears as Marcianus 299 and the numerous manuscripts copied therefrom. The original seventh century collection was probably copied before all of these mutilations had occurred, and numerous later texts were added to the copy: the result was the manuscripts Parisinus Græcus 2325 and 2327 and their numerous copies. The filiation of these manuscripts has been a matter of controversy, but the above summary is not far from the truth.

Most of the Greek alchemical writings are edited and translated in Berthelot's invaluable *Collection des Alchemistes Grecs* (Paris, 1888), which, however, omits the work of Stephanus, which is found in Ideler's *Physici et Medici Græci Minores* (Berlin, 1841). Berthelot also omits the alchemical poems: these are to be found in Fabricius, *Bibliotheca Græca* VIII (1802) and in Goldschmidt's *Heliodori Carmina Quattuor* (*Religionsgeschichtliche Versuche und Vorarbeiten* XIX, 2, Giessen 1923).

The chemical Papyri have been published by O. Lagercrantz, *Papyrus Græcus Holmiensis* (Upsala, 1913) and by Berthelot (*Archéologie et Histoire des Sciences,* Paris, 1906).

An examination of the miscellaneous collection of Greek alchemical texts enables us to classify their authors with fair certainty into (1) those who wrote before Zosimos of Panopolis (*c.* A.D. 300) formed his great collection of alchemical material, and (2) the authors later than Zosimos; these latter produced little else but commentary. Zosimos himself occupies an intermediate position, being at once an original author and a commentator on earlier works.

These early writings are of exceedingly diverse character. Some are very practical laboratory treatises: others are almost wholly mystical. It is not possible, as might have been hoped, to trace mystical and practical Alchemy to a single source. Rather, as we approach the earliest texts, we find a more definite division between these aspects of the Art.

THE CHEMICAL PAPYRI

Almost wholly practical are the papyri of Leyden and Stockholm. The authors of these are unknown, but the format and calligraphy indicate that they were written towards the end of the third century A.D. They contain some hundreds of recipes for the preparation (or falsification) of gold, silver, asemos, precious stones, and dyestuffs. It is interesting that these should be lumped together in a single treatise, and it is clear that the colouring of a metal so as to imitate gold or silver was thought of as fully analogous to the dyeing of a piece of cloth.[5]

How did the authors of these papyri try to make gold and silver? Here is a recipe:

> Asemos[6] one *stater* or copper of Cyprus 3 *staters;* 4 *staters* of gold; melt them together.

In other words, turn 24-carat gold into 19-carat or 10-carat gold. This type of recipe is common enough. It seems that it was thought of not as a mere mixing, say, of gold and copper, but as an increase of the quantity of gold at the expense of its quality. Here is a less crude recipe:

> To increase the weight of gold, melt it with a fourth part of cadmia. It will become heavier and harder.

Cadmia was an impure mixture of oxides of such metals as copper, arsenic, etc., obtained from copper smelters' flues. The effect of the process would be to smelt this to base metal, which would mix with, debase, and augment the gold.

[5] For the further development of this notion, see Arthur John Hopkins "Earliest Alchemy," *Scientific Monthly,* VI, 1918, 530-7; "Bronzing Methods in the Alchemistic Leyden Papyri," *Chemical News,* LXXXV, 49; *Alchemy, Child of Greek Philosophy,* Columbia University Press, 1934.

[6] This word in modern Greek simply means "silver"; in the works of the alchemists it seems to mean a "white silver-like metal."

These papyri contain a great variety of other recipes for gold-making. "Gold" is made not only by debasing genuine gold as described above, but also by surface treatments. Thus base gold objects were heated to redness with iron sulphate, alum, and salt. These evolved sulphuric and hydrochloric acids which removed the base metals from the surface of the gold, leaving a thin layer of pure gold which, after polishing, made the whole object look like pure gold. Other recipes describe gilding.

An interesting and primitive recipe runs:

> *To give objects of copper the appearance of gold* so that neither the feel nor rubbing on the touchstone[7] will discover it; particularly useful for making a fine-looking ring. This is the method. Grind gold and lead to a dust fine as flour; 2 parts of lead for one of gold, then mix them and incorporate them with gum, coat the ring with this mixture and heat. This is repeated several times until the object has taken the colour. It is difficult to discover because the rubbing gives the mark of an object of gold and the heat consumes the lead[8] and not the gold.

Gilding with an amalgam of mercury and gold in the modern style is also described. A number of recipes describe gums or varnishes or dye-liquors to tint metal superficially in the style of a lacquer, and numerous methods of making gold-coloured paints or inks with various yellow lacquers and pigments are described.

Much attention is also given to the making of silver and "asemos," a white alloy resembling silver. Here is a recipe for making silver:[9]

> Take copper which has been prepared for use and dip it in dyer's vinegar and alum and leave it to soak for three days. Then melt one *mina*[10] of the copper, some Chian Earth and Cappadocian salt and

[7] A hard black stone on which the gold was rubbed, leaving a bright metallic streak. The colour and extent of the streak enables an expert to judge the purity of the gold.
[8] *i. e.*, oxidizes it to litharge, which melts and runs off.
[9] *Papyrus Holmiensis* (1st recipe).
[10] 1 mina = about 1 lb. = 100 drachmæ.

flaky Alum up to six drachmæ. Smelt it carefully and it will be excellent. Add not more than 20 drachmæ of good and tested silver, which will make the whole mixture imperishable (untarnishing).

The process is, first, a superficial cleaning of copper (the mixture of alum and vinegar is very effective). Next the copper is melted with a kind of fuller's earth and with salt and with "flaky alum" which in the works of the alchemists is used, in some places, for a composition containing arsenic. A *careful* fusion (in order not to drive off all the arsenic) gives a white or whitish-yellow copper-arsenic alloy. By fusing this with silver a brilliant white alloy of, perhaps, 77 per cent copper, 19 per cent silver, and 3 per cent arsenic would be obtained.

We find in these papyri very clear evidence that attempts to make gold and silver, sometimes genuine and sometimes fraudulent, were being carried out in Egypt before A.D. 300. We should say that these papyri were the work of alchemists were it not that their gold-making is treated as an entirely matter-of-fact and practical process. There are no hints of revelations from gods or of traditions from ancient philosophers. There is no concealing of methods under symbols and no rhapsodies about the divine character of their art. None the less these papyri are the earliest *documents* which reveal the idea of making precious metals; the methods they use, moreover, are very like those of one of the groups of early alchemists. We cannot regard these papyri as the source from which true Alchemy developed, for one of them mentions the alchemist "Demokritos"; but they give us the valuable information that practical goldsmiths were trying to make gold and silver in Egypt not long after the time when the first alchemists were writing.

These papyri are not in the direct tradition of Alchemy. They are nowhere quoted or alluded to by an alchemical author, and they lack the spiritual aspect always present in Alchemy.

THE EARLIEST GREEK ALCHEMICAL AUTHORS

The truly alchemical texts of the Græco-Egyptian period include much that is earlier than A.D. 300. These early texts are attributed for the most part to lofty sources. Demokritos, Isis, Iamblichos, Moses, Ostanes, Eugenios, Maria, Kleopatra, Agathodaimon, Komarios, Hermes, Pammenes, Chymes, Pibechios, Petasios are the names we find attached to early alchemical texts. The character of these texts precludes any possibility of the attributions to the historical Demokritos, Iamblichos, Moses or Kleopatra being correct: the attributions to supernatural personages need not be discussed: the other authors—Eugenios, Komarios, Pammenes, Chymes, Petasios—cannot be identified with any known personage. Many of the early texts are anonymous. It seems likely that the sources of all these texts are concealed by pseudonyms: this is only to be expected in view of the secret character of early Alchemy, and also of the respect which antiquity conferred upon alchemical writers.

THE SCHOOL OF DEMOKRITOS

The most important of these early alchemical writers was Demokritos. The style and content of the texts preclude their having been written by Demokritos of Abdera (d. 376 B.C.), but their ascription to him is readily understood, for a considerable pseudonymous literature attaches to his honoured name. The alchemical author who took the title of Demokritos wrote before A.D. 250, as is witnessed by his mention in the Stockholm and Kenyon papyri: Zosimos (third to fourth century) mentions him as an ancient author, so an ascription of his work to the second century A.D. is reasonable. His successors regard him as *The Philosopher,* inferior perhaps to Hermes in prestige, but superior in lucidity and scope. Two works attributed to him survive—the *Physical and Mystical Mat-*

ters and the *Book Addressed to Leukippos*. He certainly wrote many other books, which are freely quoted by Zosimos.

The *Physical and Mystical Matters* is obviously a composite work. It opens with two very practical recipes for dyeing cloth purple; these closely resemble the recipes contained in the chemical papyri. The style then abruptly changes to one which is best characterized by quotation:

> Recollecting these ideas of our ordained master and knowing the diversity of matter we endeavoured to bring the natures into harmony. But as our master died before we were initiated and at a time when we had not attained the complete knowledge of matter, we were told that we must evoke him from Hades. And as I set out to do this, I called upon him directly in these words. "Grant me gifts, in return for that which I have accomplished for you," and having thus spoken, I kept silence. And as I called upon him many times, asking now how I should harmonise the natures, he told me that it was difficult to speak without the permission of the daemon. And he only said "The books are in the temple." Returning to the temple I set myself to search if by chance I might gain possession of the books: for when he was alive he had said nothing of them. For he died leaving no testament, having, as some say, taken poison to separate his soul from his body; or better, as his son says, having taken poison in error. Before his death, he had intended to show the books to his son alone when he had passed his first prime. None of us knew anything about these books. As after a search we found nothing, we were most anxious to know how the substances and natures were made one and combined. As we had completed the combination of matter, and it was time for a ceremony in the temple, we made a common feast. Then as we were in the temple one of the columns suddenly opened but we saw nothing within. For neither he nor anyone had said the books of his father were hidden there. Advancing, he led us to the column: leaning forward we saw with astonishment that nothing had escaped us except the precious formula which we found there:
>
> "The Nature rejoices in the nature and the nature conquers the nature and the nature masters the nature."

We were much surprised that he had summed up all his writings in so few words.

I come[11] also bringing into Egypt the treatise on Natural things so that you may raise yourselves above the curiosity of the vulgar and the confusion of matter.

Thereafter the mystical atmosphere is dispelled and we return to the perfectly practical and sensible recipes—allied to those of the chemical papyri—by which the author proposes to make gold and silver. Similar abrupt transitions are found in many early texts, and it is difficult to resist the conclusion that practical treatises, not much unlike the chemical papyri already described, have been dressed up in these fantastical garments to gain the respect of later mystical alchemists. The rest of the book is divided into two parts, the *Chrysopœia* or book of gold-making and the *Argyropœia* or book of silver-making.

The recipes included in these are not in the least arcane in character, but are essentially practical methods of making gold-like and silver-like alloys. They are obscure, not through any intention of the author, but on account of our difficulty in identifying the materials and elucidating the technical procedure. The mystical commentator breaks in again in a later part of the text, but disappears again equally abruptly. It is very clear that the text of the *Physical and Mystical Matters* is composed of two separate parts, physical and mystical.

A reading of the Greek alchemical texts reveals that there are three others, not attributed to Demokritos, which resemble the *Physica et Mystica,* first in the character of their recipes and secondly in their ready separation into a practical content and a mystical or supernatural ascription. These are the *Work of Isis Addressed to Horus,* the *Chemistry of Moses,* and the four small works attributed to Iamblichos. Thus the work attributed to Isis has a long mythological exordium followed by very practical recipes with no trace of Egyptian or other mystical symbology. The work

[11] This appears to be the beginning of the original treatise, to which some later author has added the high-flown introduction.

attributed to Moses has a short prelude based on Exodus, xxxi and xxxvi, followed by wholly practical recipes. It is obviously a compilation and contains recipes taken direct from the works of Demokritos. A seventh or eighth century author refers to "our treatise dedicated to Moses," thus affording evidence that the ascription to the Hebrew prophet was made at a very late date.

Finally the work attributed to Iamblichos also derives in part from that of Demokritos, and there is no trace of anything save the name Iamblichos which would warrant its attribution to that philosopher.

Zosimos (*c.* A.D. 300) quotes Demokritos freely, but makes no mention of Isis or Iamblichos, and in only one passage, of doubtful authenticity, speaks of Moses: it seems reasonable then to suppose that the ascriptions to the last three had not been made in the third or fourth century. The voluminous commentator Olympiodoros (fl. *c.* A.D. 425) makes no mention of them.

It may then be justifiable to postulate a "DEMOCRITAN TREATISE" containing the practical recipes of the *Physical and Mystical Matters* and of the works of Isis, Iamblichos, and Moses, but not their mythological or pseudo-historical exordia and interpolations. This treatise would be a work similar to, but more elaborate than, the papyri of Leyden and Stockholm, and dealing with the same subjects, the artificial preparation of gold-like and silver-like alloys, and the dyeing of purple. This hypothetical treatise may be regarded as one source of Greek Alchemy.

Two features of early Alchemy are, however, notably absent from it. These are, first, the use of elaborate apparatus for distillation and sublimation and, secondly, the mystical content which distinguishes alchemy from mere metallurgy. Sources at least as early as that of the "Democritan Treatise" can be found for these elements in Greek Alchemy.

The works which we have conjectured to be the *débris* of the Democritan treatise mention very few pieces of chemical apparatus. It is probable, but not certain, that distillation was known to Demokritos; sublimation was, however, certainly employed by him.

THE SCHOOL OF MARIA

In the works of the Greek alchemists there appear for the first time the familiar apparatus employed for distillation; and in addition several types of complex apparatus, probably of the reflux type, are described.

The importance of these is best indicated by the illustrations,[12] in considering which it must be remembered that nothing whatever of the character of specifically chemical apparatus has been found in texts earlier than these, and that they show us the birth of practical chemistry. The drawings have, of course, been copied in the tenth or fifteenth century, and doubtless have been more than a little mutilated and distorted. They correspond, however, in all important respects with the descriptions in the texts.

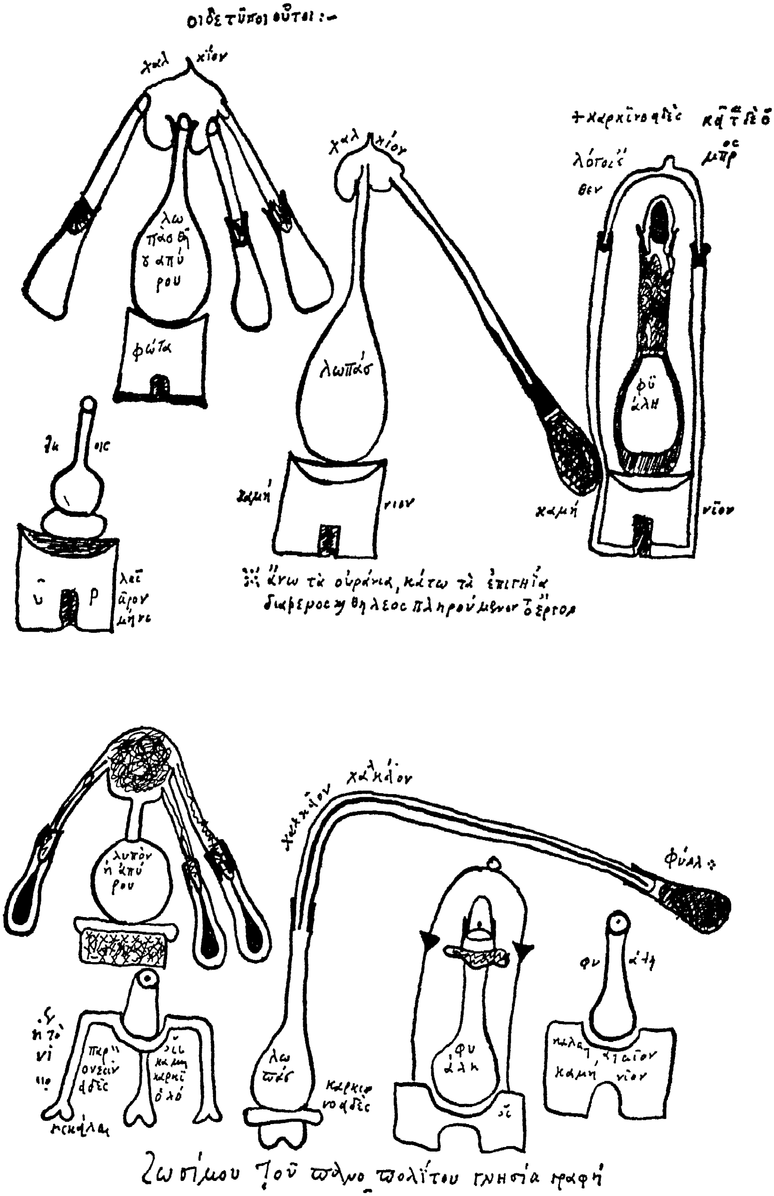
The upper half shows a flask, alembic, condenser, and receiver, and also a form of reflux apparatus. The lower half shows distillation apparatus, tripod, reflux apparatus, "handsbreadth furnace," waterbath or ashbath. The next illustration shows a distillation apparatus of very modern type.

It should be remembered that the nearest thing to distillation mentioned by classical authors is the condensation of steam in a sponge (Aristotle) and the condensation of mercury on a pot-lid (Dioskorides).

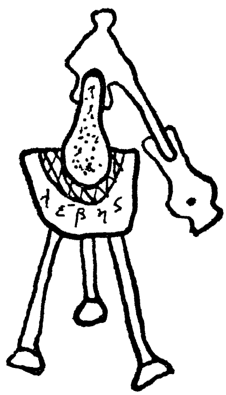
From Egypt, however, has come a doubtful hint of an earlier use of distillation apparatus. Two objects discovered at the Bucheum, close to the Egyptian town of Hermonthis, mentioned in our texts as a place where alchemy was practised, somewhat resemble still-heads, but the angle of the side-tubes suggests that they are probably enemas, or funnels used in the embalming of bulls. They may date from 200 B.C.

The *kerotakis* apparatus is peculiar to Greek Alchemy. The word

[12] These and other drawings from Greek MSS. appear in Berthelot's *Introduction à l'Étude de la Chimie des Anciens et du moyen Âge*, pp. 104-172.


οἱ δὲ τύποι οὗτοι :-
λωπάς
ἄνω τὰ οὐράνια, κάτω τὰ ἐπίγεια
Ζωσίμου τοῦ Πανοπολίτου γνησία γραφή

means an artist's palette; the Greek painter's medium was wax, and his colours had therefore to be kept hot on a palette rather like a bricklayer's trowel. This was heated on a little stove. The *kerotakis* apparatus used by the Greek alchemists seems to have been a triangular palette on which metals were exposed to the vapours of sulphur, arsenic, or mercury. The apparatus always comprised a furnace, a place where the volatile substance was heated, a palette to support the metals and a condensing cup to condense and return the vapours. Its utility as a means of gold-making is very difficult to picture.



The passages describing all these types of apparatus are, with rare exceptions, to be found in the works of Zosimos and later commentators. It would appear that Zosimos was in the habit of using apparatus of this type, but that he did not devise it himself, and regarded the works of the Jews, especially those of Maria the Jewess, as the source of his information. He repeatedly quotes Maria's descriptions and directions. It may be noted, in passing, that in this early age of Alchemy women were prominent in the Art. Maria the Jewess, the alchemist Kleopatra, Theosebeia the sister of Zosimos, and Paphnutia the Virgin are mentioned. All four belong to the first three centuries of the Christian era.

The works of Maria are unhappily lost, but are quoted freely by Zosimos, who tells us that a great number of pieces of apparatus were devised by her, especially those of the *kerotakis* type, and also furnaces. The most extensive passage quoted by him reveals Maria as a practical chemist, and confirms our belief that the name Maria is not a mere ascription, but is that of a real woman who knew the interior of a kitchen. Zosimos[13] quotes her:

> "Make" she says, "three tubes from ductile bronze, thin metal in thickness little more than that of a frying pan for cakes, in length a cubit and a half. Make three such tubes and make one of the diameter of about 3 inches adjusted to the opening of the copper still-head. Let the three tubes have openings adapted to their little receivers; let there be a little nail for the thumb tube so that the two finger tubes may be adapted to the two hands from the sides. Near the edge of the copper still-head are three holes adjusted and let it be soldered to fit closely to that part which carries the vapour upwards in the contrary direction. And placing the still-head on the earthenware flask containing the sulphur and having luted the joints with flour paste, put large glass flasks on the ends of the tubes, so thick that they will not break with the heat of the water carried up the middle."

The description corresponds closely to a pictorial representation reproduced from Marcianus 299 by Berthelot, *Introduction,* p. 139, fig. 15.

Maria was not a contemporary of Zosimos: we must therefore regard her works and "the books of the Jews" as the source of the chemical technique appearing in these texts. It is stated in these texts that the Egyptians initiated the Jews into these alchemical secrets. Conformably to this, the only early author other than Maria who speaks of this apparatus is Agathodæmon, who writes as if from Memphis. Zosimos, moreover, writes to his sister Theosebeia, saying he has seen an ancient furnace in a temple at Memphis, and then goes on at once to quote Maria about distillation apparatus.

[13] *On the Tribikos and the tube:* Berthelot, *Collection,* p. 236.

The degree of credence to be afforded to such statements is a matter for individual judgment.

Maria was not only concerned with distillation. Her alchemical method is distinct, but most obscure, apparently being based on the treatment of copper and lead in the *kerotakis* with arsenical or sulphurous vapours. Her work had also some mystical content, her chief maxim being "Join the male and the female and you will find what you seek." The greater part, if not the whole, of practical Greek alchemy derives from the Democritan treatises and the lost works of Maria.

THE MYSTICAL TEXTS

The symbolic and mystical part of alchemy seems to derive in the main from other sources.

Certain texts, we have seen, have preludes and interpolations concerned with the supernatural. These have no direct bearing on alchemical procedure, but merely indicate the lofty source of the quite mundane matter which follows. The works of Demokritos, Isis, and Moses belong to this class.

Another class of text is truly symbolic, describing what may be a practical or a mystical process in terms of symbols which cannot be given a literal interpretation. The most important of these texts are the early and fragmentary *Dialogue of Komarios and Kleopatra* and *Dialogue of Kleopatra and the Philosophers,* quotations from which appear below, and the page of symbolic pictures entitled the *Chrysopœia of Kleopatra.* Somewhat similar are the remarkable text of the book of Ostanes addressed to Petasius, the texts dealing with the Serpent Ouroboros and the obscure but impressive Visions of Zosimos (pp. 88-92 of this number).

To these must be added a number of short fragments, oracles of Apollo and Orpheus, fragments of the lost works of Hermes, etc.

In connection with these texts the question must necessarily arise as to whether their content is to be interpreted as a symbolic de-

scription of human regeneration or as a symbolic description of a metallurgical process. The question can only be settled by a careful study of the texts, and no doubt the two aspects are not mutually exclusive.

The central themes of the works attributed to Kleopatra are the Unity of All Things, and Death and Revivification by a symbolic Water.

The *Chrysopœia of Kleopatra*[14] indicates these notions briefly. It consists simply of a page of symbolic drawings. In the centre of the Serpent Ouroboros who eats his tail are the words "Ἓν τὸ πᾶν"—"One is all." Another emblem contains the symbols of gold, silver, and mercury enclosed in two concentric circles, within which appear the words *"One is the serpent which has its poison according to two compositions"* and *"One is All and through it is All and by it is All and if you have not All, All is Nothing."* A distillation apparatus is clearly figured, and also other alchemical apparatus and symbols not clearly understood.

A quotation may show the character of the text of the *Dialogue of Kleopatra and the Philosophers:*

> Ostanes and those with him answered and said to Kleopatra:
> "In thee is concealed a strange and terrible mystery. Enlighten us, casting your light upon the elements. Tell us how the highest descends to the lowest and how the lowest rises to the highest, and how that which is in the midst approaches the highest and is united to it, and what is the element which accomplishes these things. And tell us how the blessed waters visit the corpses lying in Hades fettered and afflicted in darkness and how the medicine of Life reaches them and rouses them as if wakened by their possessors from sleep; and how the new waters, both brought forth on the bier and coming after the light penetrate them at the beginning of their prostration and how a cloud supports them and how the cloud supporting the waters rises from the sea."

And again:

14 Berthelot, *Introduction,* fig. 12.

> For I tell this to you who are wise: when you take plants, elements and stones, from their places, they appear to you to be mature. But they are not mature until the fire has tested them. When they are clothed in the glory from the fire and the shining colour thereof, then rather will appear their hidden glory, their sought-for beauty, being transformed to the divine state of fusion. For they are nourished in the fire and the embryo grows little by little nourished in its mother's womb and when the appointed month approaches is not restrained from issuing forth. Such is the procedure of this worthy art. The waves and surges one after another in Hades wound them in the tomb where they lie. When the tomb is opened they issue from Hades as the babe from the womb.

Such passages as the above may be interpreted in detail as referring to the mystical death and regeneration of the soul, and also to the destruction of metals in the interior of the kerotakis (referred to as the Hades) and their revivification in the smelting fire. In my belief, the alchemists who wrote this text saw in the practical operations a symbol of mystical regeneration and, moreover, regarded the practical process as essentially similar to the mystical, and even perhaps as having some magical effect in promoting the latter.

The texts we have just considered centre round the idea, essential to all mysticism, of death and revivification. The later Visions of Zosimos, printed on pp. 88-92 develop the same theme. These visions have something of the quality of an actual dream and are probably not merely allegories couched in dream-form. The visions can be read equally well as a mystical process for exaltation of man, or a practical alchemical process of exaltation of metals; and as the temper of the age was far more mystical than practical, we should do very ill to reject the former interpretation.

THE SYMBOLISM OF THE SERPENT

The tail-eating serpent who must be slain is a most interesting symbol which is found in several early alchemical texts. The sym-

bolic use of the serpent is so universal a habit of religious thought that it gives no clue to the origin of the writings that make use of it. This symbolism dates back to the mesolithic (Azilian) culture, and almost every race has incorporated the serpent, at once wise and deadly, in its symbology. But the serpent of the alchemical text is Ouroboros, he who eats his tail. This symbol is much less common. The Gnostic text "Pistis Sophia" describes the disc of the Sun as a great dragon with his tail in his mouth. In the same work the notion appears that the earth is encircled by such a dragon, beyond which is the outer darkness where souls incapable of redemption are cast. Again the fourth-century writer Horapollon says that the Egyptians represented the universe as a serpent devouring its tail. The same image is often found on Gnostic gems.

The dragon or serpent is also a guardian of treasure—witness the golden apples of the Hesperides. The notion of the tail-eating dragon is, then, that of the guardian of the treasure, the Sun, the universe, within which can be written the Ἓν τὸ πᾶν. The task of the adept or of the practical alchemist alike is to destroy or dissolve this guardian of the treasure and use his corpse as a stepping-stone to the treasure itself ("Visions of Zosimus," see p. 90).

The imagery of the serpent is found in the early and strange texts attributed to Ostanes, the legendary Persian instructor of Demokritos. This text is notable for a curious symbolism.

Zosimos speaks of him as "the very ancient Ostanes," and quotes him as follows: "Another author speaks of a certain Sophar who formerly dwelt in Persia as saying 'There dwells upon a pillar an eagle of bronze which descends into the pure spring and bathes each day, thence renewing itself.' "

Again Ostanes is quoted as saying "Go towards the current of the Nile, you will find there a stone which has a spirit."

The text attributed to him has the appearance of being of early date. The first paragraphs may be quoted:

1. The unalterable nature rejoices in a little water. For mixtures (of mercury) alter it from its underlying nature. For every disease is

healed by this precious and divine water. The eyes of the blind see, the ears of the deaf hear, the dumb speak clearly.
2. Here is the preparation of this divine water. Taking the eggs of the serpent of the oak which dwells in the month of August on the mountains of Olympus or Libanus or Taurus. Put a pound of these which must be fresh in a glass vessel. Place on them, divine water, that is hot, and raise the sulphur without fire, four times into the sky until the distillate of oil is purple. Take 13 ounces of Amianthus, 9 ounces of the blood of the murex, 5 ounces of the eggs of the golden winged hawk . . .

THE SYMBOLISM OF THE EGG

The egg very naturally plays a large part in alchemical symbology, and it would indeed have been surprising if the egg, from which the living creature so mysteriously develops, had not been adopted by Alchemy, an art essentially creative. The symbol of the egg is of great antiquity. In one of the Egyptian cosmogonies Ra was produced as an egg from sky and earth, and Ptah the great artificer shapes the sun-eggs and moon-eggs on his potter's wheel. The notion reappears in the various Orphic cosmogonies which have in common the production of an egg of light (or, in some versions, of matter) from which the God emerges. In one version the two parts of the egg become heaven and earth. In the Upanišads (the *Chhandogya Upanišad*) the cosmic egg breaks into a silver half which becomes the earth, and a golden half which becomes the sky. Various parts become the mountains, rivers, seas, etc., while from the egg itself is born the Sun. In the Greek alchemical texts there appears a rather similar notion in which the parts of the egg are assimilated to various substances. These texts seem to represent a tradition independent of those already mentioned. The notion appears in Zosimos, and the texts whose substance he seems to draw on probably therefore belong to the early period of Greek Alchemy. The symbolism does not occur in the Democritan text

nor in the fragments of the work of Maria. Thus one of these[15] texts begins:

> *The Nomenclature of the Egg: it is the mystery of the Art.*
> It is said that the egg is composed of four elements because it is the image of the world and contains in itself the four elements.

The text goes on to say that the shell represents Earth and the metals; the white represents water, and the divine water; the yellow of the egg is said to be chalkanthum (vitriols); the oily part of the egg is fire.

This is, however, merely a philosophic rationalization of a primitive symbol. When Olympiodoros (fifth century) tells us that Hermes wrote of the Egg in the Pyramid: that the egg is the reproduction of the universe, and is the "world with golden hair" we may be coming nearer to the source of this symbol.

SYMBOLISM OF PLANETS AND METALS

A type of symbolism which can be traced to sources much more ancient than any we have for Alchemy is the association of metals with the planets, discussed by Prof. J. R. Partington on pp. 61-64 of this number, and need receive no further notice here. It is uncertain how early such symbolism is to be found in alchemical texts. The Leyden papyrus uses the signs of Sun and Moon for gold and silver, so that a part at least of the planet-metal symbolism was in use in the late half of the third century. The apparently early text, the *Chrysopœia of Kleopatra,* also shows these symbols, and it is fair to suppose that the adoption of the assimilation of the metals to the heavenly bodies is contemporary with the beginnings of alchemy itself.

15 Berthelot, *Collection,* I, iv, p. 20.

HERMES AS FOUNDER OF ALCHEMY

The legendary founder of the Art of Alchemy is Hermes, who, however, makes but a small appearance in the Greek alchemical writings.

Hermes Trismegistos was regarded by the Greek alchemists as a remote and lofty figure. Among the alchemical texts we find only three attributed to him. One is not alchemical, but is concerned with divination. Another is doubtfully alchemical. The third is the Enigma:

> Unless you disembody the bodies and embody those without bodies, nothing which is expected will occur.

Several quotations from the lost works of Hermes are to be found in the works of Zosimos and Olympiodoros. They tell us very little, but indicate that his works had both mystical and practical aspects, and would perhaps suggest that they were allied to the work of Demokritos rather than that of Maria.

The famous Emerald Table of Hermes is not found in Greek Alchemy, though its mention in an eighth-century Arabic text, and the existence of the Greek word *telesmus* in the Latin version hint at a Greek original. It may confidently be asserted that it was unknown to the Greek alchemists whose works survive. These do not quote it, and indeed its ideas and expression differ widely from anything contained in Greek alchemical texts.

The conjecture that the Emerald Table, and indeed much that was known by the Arab alchemists, was derived from an independent early source is a tempting one, though the evidence is too scanty to allow of anything more than speculation.

NUMEROUS INDEPENDENT SOURCES OF GREEK ALCHEMY

All the important early texts have now been considered, and it is clear that no one of these can be regarded as the original source of the alchemical tradition. The following groups of texts appear to represent different schools of alchemical thought, and there is no reason to suppose that any one of them is earlier than the others:

The Democritan Treatise. (Practical colouring of metals.)
The lost work of Maria. (Operations involving elaborate apparatus.)
The works attributed to Kleopatra. (Mystical.)
The work attributed to Ostanes. (Mystical and practical.)
The fragments of Hermes. (Mystical and practical.)
The Egg-symbolists. (Symbolic.)

It must be concluded that, at the date when these earliest treatises were written, Alchemy was already a well-developed system with several schools of thought. There is, however, no direct evidence in the Greek alchemical texts of any remote antiquity for the origin of Alchemy. The definite assertion of the texts, their place of origin, and the character of their mythology and symbolism indicate that their immediate source was Egyptian; but the acceptance of the assertion that the texts are based on secret knowledge immemorially in the possession of the Egyptian priesthood must be a matter for individual judgment. If we accord even a tentative adherence to such a theory, we may be comforted by the certainty that the evidence for any other origin of Alchemy is even more slender.

Charles Singer

GALEN AS A MODERN*

A few preliminary words on certain obvious debts of modern medicine to Galen.

Firstly, the earliest modern anatomies were based on his work. Our anatomical nomenclature is essentially his. Many of our commonest anatomical terms were taken direct from him. Some of his terms came into our anatomical vocabulary in the thirteenth/fourteenth century, most in the sixteenth century, a few since.

Secondly, he is the undisputed ancestor of experimental physiology. The very basis of modern medicine, the conception that rational treatment can be determined only by our view as to the actual workings of the body, comes to us from him. Could any higher claim be made for him as one of the moderns?

Thirdly many vegetable drugs still in use were recommended by him. Pharmacists, when they make up prescriptions, still refer to their vegetable ingredients as *galenicals*. The origin of this term is not far to seek, for the stock therapeutic textbook that was in use for many centuries was a Latin translation of one of his works. All modern pharmacopœias have been influenced by it.

* Reprinted from *Proceedings of the Royal Society of Medicine,* Vol. XLII (1949), pp. 563-70, by courtesy of the Honorary Editors of the *Proceedings of the Royal Society of Medicine,* and with the permission of the author.

But if Galen is so far a modern, it is also true that we are separated from him by a whole universe of discourse. That which especially cuts us off from him is not in the practical region of rational medicine; it belongs rather to the field of ultimate belief, of religion if you will. Whatever we think of the nature of life, we can hardly begin to understand Galen's conception of it without some philosophical discussion. His view is obscure to us because our fundamental attitude to the physical world is incompatible with his. For Galen adhered—somewhat loosely, it is true—to the Stoic creed of his master and friend, the philosopher-emperor Marcus Aurelius. The essential feature of their faith was belief in the existence of a world-spirit or *world-pneuma.* This must not be confused either with the Christian conception of *spirit* or with the chemical conception of vapour or gas. Yet Christians and chemists and Christian chemists have all made this confusion, times out of number.

The idea of *pneuma* carries with it the thought, sound, and meaning of the act of breathing. It involves, too, the idea that there is something drawn in with every breath. But what is that something, and in what sense is it "material," and what do we mean by "material"? How can these things be answered here? How many generations of philosophers and theologians have dreamed of the nature of that which God breathed into the nostrils of the first man? How many have failed to make their dreams intelligible? I will not enter the discussion of the meaning of *spirit* in Holy Writ, but the *pneuma* of classical antiquity involved a conception of the nature and meaning of breathing utterly different from our view that treats breathing as subserving the oxygen-carrying functions of hæmoglobin.

The Ancients in general and the Stoics in particular did not regard air as having weight. They knew nothing of the nature and variety of gases. Those ideas (like the word "gas" itself) date from the seventeenth century (with perhaps certain earlier adumbrations). The Stoics of old believed in a general *world-pneuma* or *world-spirit* which we all share during life, manifesting it by our

breathing. At our death, when we cease to breathe, our share passes to join again the general world-spirit from whence it was first drawn. So much can be learned from the sweetly-sad *Meditations of Marcus Aurelius,* truly and literally an *inspiring* work. There are passages in its lovely pages which make the reader draw his breath deeper.

The physiologists of antiquity, personified by Galen, had their own ways of explaining the incarnation of this spirit in the body of man. Galen would trace its transformation into the *natural spirit* which was made in the liver and was distributed by its branches, the veins; this in turn was transformed into *vital spirit* which was elaborated in the (left) heart and was distributed thence by its branches, the arteries; and this finally was transformed into *animal spirit* by the action of (the *rete mirabile* of) the brain, whence it was distributed by the nerves. We have no need to follow further the pneumatics of Galen. It is enough for the present to remember that Galen ascribed all activities of living things to such manifestations of the world-spirit. That was essential to his outlook on the organism. From that outlook he could as little rid himself as we can of our conception of the chemical action of digestive processes or the mathematical relationships of mechanical devices. In his physiological work, Galen was always dealing with some incarnation of this world-spirit. But while doing so he strove, as earnestly as any modern physiologist, to explain the actual workings, the mechanical apparatus, of the body. It is this effort that brings him among the moderns. Once we have realized this, we are no more concerned with his philosophy than we need be with the religion of a modern physiologist. Philosophy and science are on different levels of thought. Unless we can separate them we can have no science. Among the intellectual results of failure to separate them was the collapse of science after Galen and the mental confusion of the centuries that follow. Of course I do not suggest that this was the only cause of the darkness of the Dark Ages.

Galen began writing when he was 13. He wrote rapidly, easily, and constantly till he died at 70. The bulk of his works is truly

portentous. It covers, indeed it smothers, the medicine of antiquity. If we omit the *Corpus Hippocraticum,* Galen represents at least five-sixths of all the medical writings surviving from antiquity. Most of the ancient medical writers after Galen do little but repeat him. His works occupy twenty-two thick octavo volumes in the standard modern edition. In actual words Galen probably exceeds Aristotle or Plato.

It is unlikely that anyone now living has read all Galen, either in the original or in translation, nor is there any very obvious reason why anyone should. Our debt to him is great, but he was always intolerably verbose, often unbelievably credulous, and usually maddeningly repetitious. He has no literary charm. Some of what he wrote is little better than nonsense. It is hard to believe that his philosophical writings have value in themselves, but they do reflect a way of thinking that was historically significant and they are also interesting as containing certain references to the Christian and Jewish scriptures, for he is the first pagan to mention them with any knowledge or respect. Of his works as a whole it may fairly be said that had he condensed them into one-twentieth of their space, he would now be studied twenty times more frequently. But he was no condenser.

I have called Galen a *modern.* Why modern? Because his conception of disease is anatomic. All progress in medicine is ultimately reducible to anatomic terms. As men learn more of the organism, of its workings as a mechanism or as a laboratory, of the nature of its defects, diseases, and infections, their views become ever more minutely and exactly expressed in anatomic terms. That is the way of modern medicine; but it is not the way of medicine that is really ancient. In this respect consider the "Hippocratic" writings. Their authors treat the body as a mingling of the four elements, earth, air, fire and water, or rather of their surrogates, the four humours, blood, phlegm, black bile and yellow bile. The idea is traceable back to Empedocles (c. 500 B.C. - c. 430) but is doubtless much older than he. Humoral medicine is really ancient medicine. The anatomic view is relatively modern and per-

sistent adhesion to it places Galen among the moderns. When the anatomic view first became possible, we shall presently discuss.

Soon after Galen's death his anatomical and physiological works were lost to the Latin West. They remained unknown till the thirteenth century when they began to be translated into Latin. They were, however, grossly misunderstood till the sixteenth. Greek or Arabic MSS of (almost) all of them had been recovered by the Latins by the end of the fifteenth century and by about 1550 they had all become fully available in printed Latin translations. It would be easy to present the progress of medicine from then till now as an extension of Galen's line of anatomical thought as revealed in the Latin versions. For him disease was located in a particular spot or spots of the body, that is to say it must be anatomic. But to this day there linger some traces of the pre-Galenic humoral pathology. We still speak of men as "sanguine," "choleric," "melancholy" or "phlegmatic" and often find our patients "temperamental"—all merely old names for the humours and their mixture. Not long since physicians commonly spoke of the "constitutions" of their patients, that is of their humoral make-up. *Every Man in his Humour* is a title chosen by a not unknown dramatist (Ben Jonson, 1598) and we still suffer from the too *humorous* fellow. These are survivals of pre-Galenic ideas. Indeed Galen himself was far from freeing himself from these ideas, but our claim for him is that he, like us moderns, was moving away from them.

It is about as sure as anything of the sort can be that the earlier Greek writers, and notably those of the Hippocratic Corpus, had learned nothing of the anatomy of the human body by dissection. Even Aristotle (died 322 B.C.), despite his biological preoccupations, was as ignorant of human anatomy as his Hippocratic forebears. When then did medicine begin to become modern? The answer is in Alexandria about 300 B.C. There and then medicine took a step more revolutionary than any that it has taken since. It was there and it was then that human anatomy began to be studied.

For how long and where was human dissection practised in

antiquity? This question is less easy to answer exactly because Alexandrian scientific literature has been lost. Galen's medical education began in A.D. 146. He never saw a human dissection. I know no evidence that any of his teachers had done so. In Galen's study years there did, however, linger a tradition of practical anatomy. Galen knew of it at Corinth, at Smyrna and at several other East Mediterranean centres, but especially at Alexandria. The practice of human dissection had, however, ceased even there by about A.D. 100. The ecclesiastical writer Tertullian, who was about contemporary with Galen, expresses horror at human dissection but in such a way as to suggest that it was a distant memory in his day.

The word *galenos* means "calm," "peaceful" and it was his given name. It was peculiarly inappropriate to him, for he was a most contentious and bitter controversialist. We have no authority for his other name or names. *Claudius,* often attached to Galen, has arisen from a misunderstanding. Some Renaissance scholar seems to have thus misread an abbreviated epithet such as *cl.* for *clarissimus*. Claudius Galen should disappear from literature.

Galen's father Nikon was an architect, a philosopher, and man of ample means which he transmitted to his son. Galen apparently was always independent of his profession for his livelihood and he could always afford ample material for his experiments. He was born at Pergamum, one of the most beautiful Hellenistic cities, an important cultural centre with a library second only to that of Alexandria. It is referred to in the Apocalypse of John the Divine as *Satan's Throne* (Ch. II, 12-17). This, it seems to me, may be a natural metaphor for the great amphitheatre attached to the shrine of Aesculapius or for the magnificent terracing of the public buildings leading up to the Acropolis—compare "King Arthur's Seat" or "The Devil's Punchbowl." In any event Pergamum was both the seat of the greatest cult of Aesculapius in Asia Minor and also of one of the Seven Churches to which John was bidden to write. Galen must have known of the Christian and perhaps of the Jewish community there from his earliest years. Hence perhaps his knowledge of their scriptures.

Galen attended the medical school of his native town from his sixteenth to his nineteenth year and he lived three years longer at Smyrna where there was a teacher of anatomy. He then visited Corinth where he found that anatomical knowledge was fading and he completed his medical education by five years of study at Alexandria. He saw no human dissection there but he obtained a good practical knowledge of the human skeleton and in later years he recommended students to go there to study human bones. From Alexandria he returned to Pergamum where he remained for four years as surgeon to the stadium, attending the gladiators and athletes. He thus became expert in treating sprains, fractures, dislocations and wounds.

At 33 he went to Rome and settled there in practice for three years. Despite, or perhaps because of, his sound training and surgical experience he had difficulty with his professional colleagues and he came to practise rather as physician than surgeon. In A.D. 166 he left Rome for a prolonged journey in the Near East, visiting Cyprus, Syria and Palestine and his native Pergamum. He tells nothing of calling at Athens. This is a strange omission for Marcus Aurelius had endowed the school of philosophy there. His record of his journey to Palestine is rather disappointing. He returned to Rome in 169 and remained there until his death, serving under four Emperors: Marcus Aurelius (161-180), Commodus (180-192), Pertinax (193) and Septimus Severus (193-211). He was the friend of the first and the constant personal attendant of the second.

As to his works: They may be crudely divided into (*a*) general, personal and philosophical, (*b*) therapeutic and clinical and (*c*) anatomico-physiological and pathological. We are concerned here only with the third class. For historical purposes the Latin translations of these are more directly significant than the Greek originals. Very few—perhaps none—of the effective anatomists of the sixteenth century had any real facility in Greek, though there was a general pretence to Greek learning among them. The most important of Galen's works for the influence that they ultimately

exerted are the following, of which we give the conventional titles in their Latin forms:

(1) *De juvamentis membrorum* ("On the functions of the members"). It is the real foundation of modern anatomy since it was used by Mundinus (died 1318), the first modern who wrote on human anatomy. The *De juvamentis* is not a translation of any text of Galen but a Latin abstract of (2). It was made by some unknown writer in the thirteenth century probably from an Arabic version. First edition, Pavia 1516.

(2) *De usu partium corporis humani.* ("On the actions of the parts of the human body.") Latin translation by Nicolas of Reggio c. 1310. A fairly well-arranged complete textbook of anatomy and physiology containing numerous and remarkable observations and experiments. It was written before (3). It provided the basis of anatomical reading in the universities until Vesalius in the sixteenth century. First edition, Pavia 1516.

(3) *De anatomicis administrationibus.* ("On anatomical procedures.") Originally in sixteen books of which the last seven were early lost (in the original Greek) and therefore failed to influence anatomy. The first nine were printed in Greek at Paris in 1531, and translated into Latin by Guenther of Andernach and printed at Paris in the same year. It made a deep impression on his pupil Vesalius and formed, with (2), the foundation of his work and, through him, of modern anatomy. The *De anatomicis administrationibus* is really a laboratory handbook of actual anatomic findings.

(4) and (5) *De venarum arteriarumque dissectione; De nervorum dissectione.* ("On the dissection of the veins and arteries . . . and nerves.") These small books are little but extensions of (3). Both were first translated and printed at Paris in 1526 and both were used by Vesalius.

(6) *De ossibus ad tirones.* ("On bones for students.") Important because it is the only work of Galen, and indeed the only anatomical work of antiquity, based on human material. It was first translated and printed at Paris in 1535.

(7) *De musculorum motu.* ("On the movements of the muscles.") First translated by Nicolo Leoniceno and printed in London in 1522. It forms the basis of the muscular physiology of Vesalius and with it of the whole modern science of orthopedics.

(8) *De musculorum dissectione ad tirones.* ("On dissection of muscles for students.") An excellent work in a positive modern spirit, less verbose than most of Galen's. It makes a good companion to (7) but it was not accessible until edited by Agostino Gadaldino, Venice 1550, and was therefore too late to be used by Vesalius. It thus had relatively little effect on modern anatomy.

(9) *An secundum naturam in arteriis sanguis continetur.* ("Whether there is blood in the arteries in their natural state.") Perhaps the earliest of Galen's works on experimental physiology. It was edited in Latin by Guenther of Andernach, Paris 1536.

(10) *De utilitate respirationis.* ("On the use of respiration.") Contains experiments on penetration of the pleura and artificial respiration with bellows. It became available in the Latin version of Janus Cornarius, Basel 1536.

(11) *De facultatibus naturalibus.* ("On the natural faculties.") Contains some account of Galen's physiology. Unfortunately it is exceptionally argumentative and flatulent. It first became available in the Latin translation of Thomas Linacre, London 1523. It is the only work of Galen adequately rendered into English. (See the edition of A. J. Brock in the Loeb Library, London 1916.)

(12) *De locis affectis.* ("On disordered parts," "On the sites of diseases" as we might say.) An important work which deeply affected medical ideas of the sixteenth and following centuries. A Latin translation by Guglielmo Copo appeared at Venice in 1500. (The Greek text was not printed until 1554.) It merits respect as the first attempt at an anatomical pathology.

Galen's anatomical knowledge was based on the dissection of a very large number and variety of creatures, both living and dead, apes of several species, pigs, sheep, oxen, cats, dogs, weasels, bears, mice and at least one elephant. Invertebrates were beyond him for he had no magnifying glass. Roughly speaking, we may say his

anatomy is that of the soft parts of the Barbary ape, *Macaca Inuus,* imposed on the human skeleton. His physiological experiments were made on ungulates and apes. For anatomy the ape was a good choice for the surgery of his time, which was hardly concerned with the inner organs. For ordinary surgical instruction it was better for students to have plenty of freshly killed apes than a few unpreserved human bodies. There was no way of making anatomical preparations more permanent and the mere bulk of the human body would have made dissection too slow a process to be effective. Perhaps even in the sixteenth and seventeenth centuries much anatomy would have been better taught on apes.

Galen exhibits a quite surprising knowledge of comparative anatomy. He has a better insight into that subject, on coarse macroscopic lines, than is possessed by most medical men of our own time. He can correlate skull structure with form of foot, teeth with abdominal viscera, and so on. He knows of a considerable variety of apes and distinguishes carefully those which are dog-like—the baboons—from those which have a human form—the macaques. He knows how the differences in the gait of the two types can be expressed as differences in the skeleton and musculature of the lower limb. Among "man-like apes" he distinguishes those with tails and those without. This latter class, which he describes, does not include the "Anthropoids" of modern zoologists but contains only *Macaca Inuus* and a few others. He had never seen an anthropoid ape and statements to the contrary that have been made are due to misunderstanding.

He probably practised mostly on tailed apes, much like the organ-monkeys of our time. These were common in the markets of Rome where his experimental work was done. His favourite form was, however, the tailless Barbary ape, *Macaca Inuus*. A word may be in keeping here as to this scientific term. *Inuus* is a name of the god Pan. By exception to the usual rule of specific names, it is not an adjectival form in agreement with the generic name but a proper name in apposition to it. The accepted designation dates from Lacépède (1799). It corresponds in part to

the *Simia sylvanus* of Linnaeus (1758). To me it seems probable that Galen was usually forced to rely on one of the species of Indian macaques which were commoner, even in his time, hardier, more tolerant of captivity and much easier to handle than his favourite Barbary ape.

It is not my purpose to discuss Galen's anatomical terms, but there is one on which perhaps it is well to warn the reader, for it is very misleading. It is sometimes said that Galen failed to distinguish nerves from tendons. This is not the case, but he did hold to a false physiological theory of the nature of tendons which has confused modern readers. In the translations of his texts the Greek word *neuron* (Latin *nervus*) is sometimes translated "tendon" or "sinew" and sometimes "nerve." Now there is a reason for this. Galen saw that a nerve passes into each muscle and he traced its divisions till they disappeared from sight. He also saw that many muscles terminate in a whitish cord or tendon. He wrongly thought that the branches of the nerves reunite within the muscle to form this structure which he naturally also called *neuron*. His error entails considerable strain on the translator who wishes to be both faithful to his original and intelligible to his reader. Similarly the translator has to contend with the difficult terminology of Galen's pneumatic views.

Of Galen's actual physiological discoveries we have space to refer only to two. Deservedly the most famous is that of the Recurrent Laryngeal Nerves and their action. Indeed his whole section on the voice and its organs in the *De usu partium* (Book VII, Chapters 11 to 18) is among the glories of experimental biology. Incidentally Galen, who seldom fails to praise himself, here exults at immense length over those whom he has there refuted. These held, with the Ancients, that the voice came from the lungs *via* the trachea. The voice of a patient having been injured by an operation (apparently on the thyroid) Galen demonstrated the course of the recurrents on a living pig, tying them, releasing them, and finally cutting them. He compared the course of the recurrent

nerves to that of a runner round a turning post. Through his metaphor they have come to bear the name *recurrent.*

For his experiments on the spinal cord I can do no better than repeat the words of the late W. G. Spencer:[1]

"Galen here employed monkeys, also young pigs in which he was able to cut through the spines and laminæ with a strong knife. In monkeys he passed a fine, flat-bladed knife between the laminæ, so as to cut across the cord transversely. To divide the spinal cord longitudinally, after removing spines and laminæ, he raised the *dura mater* on a hook so as to incise it without wounding the *pia mater.* He then could cut the cord exactly along the middle line with a fine knife; there was no disturbance of function, neither the intercostal nerves nor the nerves to the hind limbs were paralysed.

"When the cord was divided transversely, the nerves connected with the spinal cord below the division lost the function both of sensation and of motion. If the section was at the level of the sacrum, sensation and motion were lost in the foot, and as the section was made higher up, so there was loss of sensation and of motion in the thigh, the hip and lumbar region. When the section was made at the level of the thoracic vertebræ, the forcible respiratory movements of the animal began to weaken. When the section was just below the middle of the dorsal region, movement continued in the upper intercostals, the upper accessory muscles of respiration and the diaphragm. Galen also noticed that the *Serratus posticus inferior* has a high nerve supply, an observation only confirmed in recent years.

"In monkeys, so long as the section was below the second intercostal space, power in the arms was preserved. A section just above this level caused loss of sensation in the skin of the axilla and inner side of the arms, i.e., in the distribution of the intercosto-humeral nerves. The hands of the monkey were weakened when the section

[1] W. G. Spencer, *Animal Experiments and Surgery,* Hunterian Lectures, London, 1920. By kind permission of the Royal College of Surgeons of England.

was made at the level of the first rib. When the section was between the seventh and eighth cervical vertebræ, the forearms were weakened but the action of the accessory muscles of respiration continued. By a section at the level of the fifth cervical vertebra the arms were completely paralysed; the diaphragm continued in full movement, also the scaleni, whilst all the intercostal movement was lost."

Galen's career presents a unique phenomenon in the history of science and one perhaps unique in cultural history as a whole. Nearly every exhibition of human activity seems to go through a process of development, flowering, and decline. The Ancients, even the most scientific of them, were not generally great hands at experiment, and Galen represents the climax and flower of the experimental spirit in antiquity, certainly so far as the biological disciplines are concerned. He brought experimental physiology to a very high standard indeed, but he was quite without successors. There is no fading out of physiological activity. It simply disappears. Yet Galen was no solitary worker; he was constantly demonstrating his experiments to large audiences of colleagues and he had many pupils, but he had no followers or imitators. Ancient science fell dead with Galen.

Why was so triumphant a scientific career devoid of successors and even of imitators? This cannot be answered completely, but some inkling of the form that the answer will one day take may perhaps be reached by considering the intellectual associations of his age. The intellectual climate was certainly against experiment. The prevailing philosophy of the educated classes in Italy was Stoicism. This gave no warrant for or encouragement to the investigation of Nature. True, Galen's own thought was based on Stoicism, but he was neither an orthodox Stoic, nor had he the characteristic Stoic temper. The outlook of the Stoic was essentially fatalistic. It had developed a close alliance with the "astrology" of the time. In those days astrology was no idle superstition but a natural development of the ancient cosmology. It had crystallized into a rigid system of beliefs concerning the nature of events on

our Globe under the mechanical working of the heavens that surrounded it. Man was enclosed within a spherical machine. Against it he could do nothing and all that he was and did and became was determined by it. There was a Supreme Power, but He was no pitying God nor would He control that pitiless machine. Perhaps God was the Spherical Universe itself. Why then should man seek to know farther the minor details of that machine? Far better, in our earthly span, to turn to things of the mind. That is the temper of Marcus Aurelius. It is no mood for the investigation of Nature.

Epicureanism, the school of philosophy that was the great rival to Stoicism, was on the wane in Galen's time. It was no more friendly to the investigation of Nature. No investigator of antiquity is known to have professed the Epicurean creed. In practice Epicureanism was even more dogmatic on the unprovable structure of the universe than was Stoicism.

Putting aside the host of trivial cults, the third great competitor for the minds of men had also come, like the philosophies, from the East. As to whether the Christian faith was unfriendly to the investigation of Nature we need not discuss here. It certainly turned men's minds away from observation and away from experiment and fixed them on the inner world. Tertullian (c. 155-c. 222), the earliest of the Church writers of the West, besides studying as a youth in Rome, spent some five years there (c. 190-195) just at the time when Galen was at the height of his reputation. Tertullian had full command of Greek philosophical literature and from that he passed to the medical works, and yet he makes no mention of Galen. As his thought developed he ceased to take any interest in the investigation of Nature except to oppose it. Dissection he despised and hated.

All the thought of the time was thus against Galen's experimental ways. But there was something within Galen as well as outside him that discouraged the further development of investigation. We have spoken of Galen as a modern but there is in him that which, rightly understood, would have closed the book of science forever. It lies in certain of his philosophical assumptions.

The point comes out best in his best known work *The uses of the parts of the human body*. There he seeks to show that the bodily organs are so well constructed and in such perfect relation to the functions to which they minister, that it is impossible to imagine anything better. Thus, following the Aristotelian principle that Nature makes naught in vain, Galen seeks to justify the form and structure of every organ, with reference to the functions for which he believes it is destined. We are thus in the presence of a work that is not, strictly speaking, on Anatomy and Physiology, but in which those sciences subserve a particular doctrine and are used to justify the ways of God to Man. We have, in fact, an extreme case of the thesis of Final Causes applied to the organism.

Galen thus holds that it is possible to discover the end served by each part which, being perfectly adapted thereto, could not be constructed other than as it is. To say this is to go even further than the *Bridgewater Treatises* which undertook, more than a hundred years ago, to demonstrate "the Power, Wisdom and Goodness of God as manifested in the Creation." It is to claim that in any work of Creation, and in every detail of such work, we can actually possess ourselves of knowledge which will enable us to demonstrate God's purpose. The acceptance of any such claim would involve cessation of all interest in investigation. Research would not be worth while because all of consequence that it could reveal would be already known. This was, in fact, the position of the early Church which did not deny the data of science but regarded them as irrelevant and trivial. Extremes had met. The teleology of Stoicism and the teleology of the rising faith of Christianity both turned men's eyes away from the material world. Galen was thus the last ancient as he was the first modern experimental physiologist.

Israel E. Drabkin

AN APPRAISAL OF GREEK SCIENCE*

Despite the increased attention that has been given, in comparatively recent years, to the history of science and to the history of Greek science in particular,[1] the opinion is still prevalent in many quarters that the scientific aspect of the Greek genius is only of secondary importance. In the Hellenic period, it is held, patient and detailed observation and explanation of phenomena were neglected for philosophical and metaphysical speculation as to the ultimate constitution of matter and of the universe; while in the Hellenistic and subsequent periods, when more attention was devoted to the special sciences, organized experiment, it is held, was rarely undertaken and, in any case, very little progress was made toward the discovery of those quantitative relations with which modern experimental science so largely concerns itself. There is, of course, an element of truth in these views, and certainly they

* Reprinted from *Classical Weekly,* XXX, 6 (1936), pp. 57-63, with the permission of the author.

[1] Complete bibliographical material may be found in: George Sarton, An Introduction to the History of Science, Volume I (The Carnegie Institution of Washington, 1927), supplemented by the Critical Bibliographies regularly appearing in Isis; P. Brunet and A. Mieli, Histoire des Sciences: Antiquité (Paris, Payot, 1935).

have not been confined to superficial thinkers. Thus Alfred Whitehead writes (Science and the Modern World, 10):

> The Greek genius was philosophical, lucid and logical. . . . Their minds were infected with an eager generality. They demanded clear, bold ideas, and strict reasoning from them. All this was excellent; it was genius; it was ideal preparatory work. But it was not science as we understand it. The patience of minute observation was not nearly so prominent. Their genius was not so apt for the state of imaginative muddled suspense which precedes successful inductive generalization.

And George Santayana (Reason in Science, 4-5):[2]

> The first period in the life of science <i. e. the Greek period> was brilliant but ineffectual. . . . Men of science were mere philosophers. . . . No scientific tradition could arise, and no laborious applications could be made to test the value of rival notions. . . . Another circumstance that impeded the growth of science was the forensic and rhetorical turn proper to Greek intelligence. . . . Worse influences in this field could hardly be imagined, since Plato's physics ends in myth and apologue, while Aristotle's ends in nomenclature and teleology.
>
> All that remained of Greek physics, therefore, was the conception of what physics should be—a great achievement due to the earlier thinkers—and certain hints and guesses in that field. . . .
>
> At its second birth <i. e. the Renaissance period> science took a very different form. . . . It was a patient siege laid to the truth which was approached blindly and without a general, as by an army of ants; it was not stormed imaginatively as by the ancient Ionians, who had reached at once the notion of nature's dynamic unity, but had neglected to take possession, in detail, of the intervening tracts, whence resources might be drawn in order to maintain the main position.

The danger in views such as those I have just quoted lies in the emphasis placed upon only one aspect of the scientific activity of

[2] See also Henry O. Taylor, Greek Biology and Medicine, 42 (Boston, Marshall Jones Company, 1922).

the Greeks, i.e. the consideration of those larger questions where science and philosophy merge. I shall try in what follows to show that, although of the greatest importance, this is a very incomplete view of the science of the Greeks and should not be made the sole basis of a comparison between Greek scientific thought and the scientific thought of subsequent ages. An embracing view of the subject would include the whole development of approximately a thousand years, and would be concerned not only with the working of the mind of the Greek scientist-philosopher grappling with the basic questions of existence and reality, of the infinite and the infinitesimal, of continuity and discontinuity, of determinism and chance, of change and persistence, of space and time, of substance and form, but would consider also the working of the mind of the Greek scientist seeking to find order in the motion of heavenly bodies, or to discover the size and shape of the earth, or the distance of sun, moon, and stars, or to understand the phenomena of lever, pulleys, vibrating strings, floating bodies, falling bodies, projected bodies, reflected and refracted light, rainbows, eclipses, and a thousand others. An embracing analysis would concern itself not only with the work of the Greek physician observing and recording the course of disease, or studying, by dissection, the functions of organs and tissues, or classifying the known species of plant and animal life, or investigating the homology of organs in various species, but also with the working of the mind of the humblest artisan as he faces the problems constantly posed by his craft and from the solution of which the application of the rational method of science may be inferred. In the nature of the case I shall not be concerned so much with a precise cataloguing of substantive achievements as with methods of attacking and answering problems and with the progress of the spirit of rational investigation.

Before we examine the work of the Greeks in the physical and experimental sciences, work which is not, as we have seen, the object of widespread appreciation, let us consider briefly a field in which the greatness of Greece is universally acknowledged, pure mathematics. But precisely in what does the greatness consist?

The growth of our knowledge and appreciation of Egyptian and of Babylonian mathematics[3] so far from dimming the brilliance of Greek mathematical achievement has given it new luster. In Egypt at least a thousand years before the dawn of Greek mathematics, problems that were by no means confined to the "practical" were posed and solved, the constancy of the ratio of the circumference to the diameter of the circle was accepted and a remarkably close approximation to its value employed, formulas stating exactly or with close approximation the areas or volumes of various geometrical figures were known; and even before this, among the Babylonians, remarkable skill had been attained in the solution of arithmetical and geometric problems leading to linear, quadratic, and cubic equations. But, so far as we know, the ideal of the rigorously deductive proof still remains the achievement of Greek mathematics. The Egyptian mathematician checked his work in the sense that he showed the solution fulfilled the terms of the problem; the Greek mathematician had, by the fourth century or earlier, attained complete control over the method of proof by axioms, postulates and a series of theorems. The Egyptian mathematician is adept at certain types of fractions, and, with their help, solves problems in arithmetic and geometric progression; the Greek mathematician goes further and works out a deductive theory of ratio and proportion which by its application to incommensurable quantities serves to clarify the problem of the irrational, and influences all subsequent thought on the subject of mathematical continuity. The Babylonian mathematician achieves brilliant results after what is,

[3] Despite great advances in our knowledge the sources are still so fragmentary that my remarks here are quite tentative. I may refer to Otto Neugebauer, Vorgriechische Mathematik (Leipzig, Springer, 1934), to the publication of the Moscow Papyrus and the mathematical cuneiform tablets in Abteilung A of Quellen und Studien zur Geschichte der Mathematik, to the penetrating studies in Abteilung B of that series, to the articles of T. E. Peet in The Journal of Egyptian Archaeology (see also the summary of Egyptian mathematics in the Bulletin of the John Rylands Library 15 [1931] 409-441), and to the editions of the Rhind Papyrus by Peet (1923) and by A. B. Chace, H. P. Manning, L. S. Bull, and R. C. Archibald (1927-1929).

presumably, an empirical discovery of correct methods; but the sense of the logically demonstrable character of correct procedure still must be placed to the credit of Greece. Not that the Greeks were unappreciative of the importance of empiricism in the *discovery* of certain types of theorems, as distinguished from their *proof*. Archimedes does not hesitate to apply the principle of the lever to aid the discovery of mathematical relations of areas or volumes, a procedure described in The Method. But the complete distinction between this procedure and deductive proof is never forgotten by the Greek mathematician. Though the debt of Greek mathematics to Egypt and the East was great, the advance beyond them was far and decisive.

In passing from pure mathematics to the substantive sciences, let us recall very briefly something of the aims and methods of the various types of science. Science seeks to find elements of order in the phenomena of nature—order in the sense of some invariant relation. This invariant relation may take the form of an invariable association of properties which permits us to recognize and to classify a particular body or a particular animal as this or that substance or as this or that species of animal. Again, an invariant relation may be found to connect two or more processes and to constitute what we generally call the relation of cause and effect, or, apart from temporal sequence, an invariant relation in the form of a mathematical equation may be found to connect, for example, the volume and pressure of gases under given conditions. For instances of all these types of order science constantly searches, but it searches also for even more comprehensive manifestations of order in nature under which the former might be subsumed, such as a theory of universal gravitation. Science discovers these invariant relations, or laws, from the most restricted to the most comprehensive type, by reasoning about that which is observed in nature. The scientist submits his guesses, hypotheses, if you will, to the test of experiment, and discards, refines, or expands his hypotheses on the basis of his observations, ever trying to see in

the particular problem a manifestation of a larger order.[4] Toward the formulation of hypotheses the scientist is aided by his knowledge of phenomena and by genius. It is this genius that enables him to see an analogy between the phenomena in question and other phenomena that have previously been dealt with successfully, or to abstract from the complexity of phenomena precisely those features which will reveal an underlying order previously not appreciated, and thus, by a change of viewpoint, to open new vistas and possibilities of conquest. Now these very elements of reason and observation, of analogy and abstraction, of hypothesis and experiment played their part in the science of the Greeks as well as they do in modern science, and on a scale by no means as restricted as certain critics of Greek science would have us believe. Finally, in ancient as well as in modern science the goal of a completely rational system embracing all nature, though never realized, is always a challenge and a guiding force.

The mutual interplay of reason and extraordinarily keen observation towards the goal of a completely deductive science based on assumptions suggested by the observations is well exemplified in the development of astronomy among the Greeks from Thales and Pythagoras to Ptolemy.[5] Not only the discoveries, inferences, and conjectures, of a substantive character, e.g. the sphericity and the size of the earth and of the heavenly bodies, the source of the moon's light, the explanation of eclipses, the obliquity of the ecliptic, and the precession of the equinoxes, but the solutions of the geometric problems involved in reducing to order the motion of the heavenly bodies, whether by systems of concentric spheres or

[4] The progressive generalization of viewpoint in science is well exemplified by the development, beginning with Greek notions, on a limited scale, of the relativity of motion and rest, toward the notion of generalized coördinates in modern physics. See S. Hessen, Die Entwicklung der Physik Galileis und ihr Verhältnis zum physikalischen System von Aristoteles, Logos 18 (1929) 339-361.

[5] See the summary of Greek astronomy to Aristarchus in Part I of T. L. Heath, Aristarchus of Samos (Oxford, 1913), and the more complete account in the first two volumes of P. Duhem, Le Système du Monde (Paris, Hermann, 1913-1914).

by systems of eccentrics and epicycles, are, and will always remain, classics of scientific thought. In this connection, it should be noted as a special achievement of Greek science that the possibility of more than one choice of coördinates by which to orient the cosmos was appreciated in some quarters and led to the notion of the earth's daily rotation about its axis (Heracleides of Pontus) and of its annual revolution around the sun (Aristarchus of Samos). That certain of the assumptions in Greek astronomical works such as Aristarchus' On the Sizes and Distances of the Sun and Moon and Ptolemy's Almagest are now, as a result of superior measuring instruments, known to be erroneous, should not at all detract from the authors' achievement from the point of view of method.

Other fields which lent themselves to organization in a deductive mathematical system based on postulates suggested by experience, and in which the Greeks seem to have laid firm foundations were optics, hydrostatics, acoustics, and certain branches of mechanics. For example, Euclid and Hero,[6] basing their analysis on the equality of the angles of incidence and reflection, an equality which experience indicates, deduce propositions with respect to images in mirrors of various shapes and combinations. Ptolemy studies refraction experimentally and finds that his measurements need only small correction to make them accord with his hypothesis as to the precise mathematical relation connecting the angles of incidence and refraction. In this search for a mathematical relation connecting two variables (angle of incidence and angle of refraction), even though the particular relation adopted is not the true one,[7] it is to be noted that Ptolemy is using methods which have been so widely applied since Galileo's time that many have failed to note that they were also applied long before. From postulates on the nature of fluids, again suggested by phenomena, Archi-

[6] Euclid, Catoptrics, Proposition 1; Hero, Catoptrics 4 (the treatise, formerly ascribed to Ptolemy, is cited from the Latin translation which is alone extant: see Hero Alexandrinus, Opera 2.324 [Leipzig, Teubner, 1900]).

[7] See the edition by G. Govi of Eugenio's (twelfth century) Latin translation of an Arabic version of Ptolemy's Optics, Introduction XXIV-XXVIII, 144.19 to end of 150 (Turin, 1885).

medes deduces fundamental propositions in hydrostatics, e.g. that a body immersed in a fluid loses a weight equal to that of the fluid displaced (On Floating Bodies, I. Prop. 7). That the results in such treatises are put in deductive form should not obscure the fact that the *discovery* of the propositions may have been quite empirical, and that in any case the adequacy of the assumptions and of the development must constantly have been tested experimentally. In much the same way the quantitative relation, discovered, it seems, by the Pythagoreans, between the pitch of a vibrating string and its length, a relation which is at the foundation of Greek musical theory, must have been, together with its consequences, the subject of experimental investigation. Again, in theoretical mechanics, the substantial progress in statics that we find, e.g., in the Mechanica attributed to Aristotle, and in the works of Archimedes, Philo of Byzantium, and Hero of Alexandria[8] presupposes wide experimental activity. Such experimental activity may have suggested and must have tested the principle of the lever and of the other machines based on that principle, and may well have suggested and tested propositions regarding centers of gravity or the composition of velocities.

I have selected these illustrations of the quantitative approach in Greek science to show the inadequacy of the view that would distinguish the Greek scientist from the modern scientist on the supposed ground that the former studied nature in its qualitative manifestations while the latter seeks to discover quantitative relationships connecting phenomena. As a matter of fact, however, what is manifested in phenomena are complexes of qualities, and science progresses when it is able to abstract from such complexes one quality for special consideration, and is able then to find some means of transforming the consideration of the quality in question (which may be, in itself, non-additive) to a

[8] E.g., Archimedes, On Plane Equilibriums; Hero of Alexandria, Machanica; Philo of Byzantium, Mechanica 4 (= Belopoiika). 20-21 (where reference is made to a treatment of the theory of the lever in a no longer extant portion of the work).

metric basis. All science involves abstraction and there is ample evidence, in all periods of Greek science, of the type of abstraction to which I refer. Often, as in the case of dynamical theory, the deficiency or sterility of the Greek development was due to the failure of abstraction to go far enough. It was abstraction in the highest degree and a looking beyond the actual phenomena that led, in the seventeenth century, to the formulation of the principle of inertia upon which could be based a fruitful dynamical theory and, as a special case thereof, a sound development in statics.

The advance of modern science has been marked by the discovery of means, of the sort I have just now indicated, which permit of the measurement of variations in qualities under investigation, devices like the thermometer, or the spectroscope, etc. The experimental use of such instruments has, in turn, made further advance in theoretic science possible. Limited though the Greeks were in the means at their disposal for various types of scientific investigation, the striving of their best representatives was basically toward the same goal as that toward which modern science strives, and was prosecuted in the same spirit and with the same basic methodology.[9] Yet in considering the contribution of the Greeks it is better to fix attention on *their* advance over their predecessors than on *our* advance over the Greeks. At all events one should be very critical of the type of general statement frequently made to the effect that the shortcomings of Greek science were due to an aptitude for the deductive as opposed to the inductive, or the static and the geometric as opposed to the dynamic and the kinetic,[10] or the

[9] Of the numerous passages setting forth, in the abstract, the aims, ideals, and methods of science, good examples are to be found in W. A. Heidel, The Heroic Age of Science, *passim* (The Carnegie Institution of Washington, 1933). The detractors of Greek science have held that in practice the Greeks did not live up to these ideals.

[10] For such a view see F. M. Cornford, The Laws of Motion in Ancient Thought, 20-28 (Cambridge, 1931), and H. Dingler, Das Experiment, 210-252 (Munich, Reinhardt, 1928). The evidence, I believe, shows the view to be entirely too broad.

qualitative as opposed to the quantitative, or the theoretic as opposed to the practical.

I should like now briefly to indicate some examples of observation, analogy, classification, and experiment in fields other than those to which allusion has already been made. The remarkably clear clinical descriptions of the course of various diseases in the Hippocratic Corpus (Epidemiae 1 and 3), the descriptions of the structure, physiology, generative processes, embryological development, and habits of hundreds of species in Aristotle's zoological works,[11] the minute descriptions of organs and tissues and their functions by Galen[12] on the basis of careful dissection, and Theophrastus' description of types of seed germination (Historia Plantarum 8.2) constitute some of the most important material, from the point of view both of substance and method, which Greek science has left us.

Of analogical reasoning on the basis of similarities e.g. between lower and higher animals, between plants and animals, between the organic and the inorganic, many examples might be cited, particularly from certain treatises of the Hippocratic Corpus.[13] I may also refer to the famous fragment of Empedocles (in Aristotle, De Respiratione 13) in which the poet seeks to explain respiration on the basis of the action of the clepsydra.

As an outstanding example of classification I may cite the classi-

[11] Charles Singer in his essay, Greek Biology and its Relation to the Rise of Modern Biology, in Studies in the History and Method of Science 2.1-100 (Oxford, 1921) takes up some of Aristotle's most penetrating biological descriptions and shows how certain facts pointed out by Aristotle have waited until comparatively modern times for rediscovery.

[12] Particularly in his De Anatomicis Administrationibus and De Usu Partium. The important anatomical work of Erasistratus and Herophilus in the third century B.C. is often referred to in Galen. On the question of the extent of dissection and vivisection among the Greeks see L. Edelstein, Die Geschichte der Sektion in der Antike, Quellen und Studien zur Geschichte der Naturwissenschaften und der Medizin 3 (1932) 100-156, as well as the pertinent material in the works cited in note 1, above.

[13] E.g. in De Semine. De Natura Pueri, De Morbis 4. On analogy, particularly in the Hippocratic Corpus, see O. Regenbogen, Eine Forschungsmethode antiker Naturwissenschaft, Quellen und Studien zur Geschichte der Mathematik, Abteilung B, 1 (1931) 131-182.

fication which is implicit in Aristotle's zoological works.[14] It is a great achievement of trained observation that on the basis of the recording of something more than five hundred species—a half million species of insects, alone, are said to be known today—Aristotle was able to classify the animal kingdom along lines which in many respects are still regarded as valid.

I have in what preceded referred at many points to experiments and the experimental method. I should like to refer to a few additional examples. The phenomena of suction were studied at a very early date in connection with the question as to the corporeality of air and the existence of a void. From elementary experiments with siphon and clepsydra began the development which culminates in the ingenious experiments and devices described by Philo of Byzantium and Hero of Alexandria.[15] The experiments described in the Hippocratic Corpus,[16] the interesting quantitative experiment of Erasistratus in which the loss of weight suffered through perspiration and respiration is measured,[17] Galen's physiological experiments to determine e.g., the mechanism of respiration and pulsation,

[14] See pages 15-20 of the paper cited in note 11, above. Note, in particular, the inclusion of Cetacea among the viviparous species (Historia Animalium 6.12).

[15] Hero of Alexandria, Pneumatica; Philo of Byzantium, Pneumatica (an Arabic version of the lost Greek text and, for certain parts, a medieval Latin version of an Arabic version are available). The atomistic approach of these authors and of various medical writers suggests the influence of Straton of Lampsacus, who combined certain features of atomism with Peripateticism.

[16] On experiment in the Hippocratic Corpus see T. Beck, Das wissenschaftliche Experiment in der Hippokratischen Büchersammlung, Verhandlung der 49 Versammlung Deutschen Philologen und Schulmänner, 197-201 (Leipzig, Teubner, 1908); A. Bier, Hippokratische Studien, Quellen und Studien zur Geschichte der Naturwissenschaften und der Medizin 3 (1932), 51-78, and the articles of G. Senn there (71, note 5) cited. Bier erroneously holds (73) that the Corpus is entirely philosophical rather than scientific, disregarding its diverse composition which exhibits many different degrees of empiricism.

[17] A bird is kept without food; the difference between the original weight of the bird and its weight at a subsequent time together with that of all visible excreted matter will measure the loss through other channels (Anonymus Londiniensis 33.45-51 [Diels]). Despite its crudeness, there is implicit in this experiment a notion of conservation of mass. At the beginning of the seventeenth century Sanctorius performs similar experiments on human beings and initiates the modern study of metabolism.

the functioning of the kidneys, the connections and mechanism of brain and nervous system,[18] are some of the many that come to mind in this connection.

Now it is quite true that, in proportion to the whole of Greek scientific literature, the part devoted to the actual description of method, observations, and conclusions in organized experimental work is small. But it is to be remembered that the publication of the results of experimental research as such, which is so important a factor in scientific progress today and which bulks large in current scientific literature, was much more restricted in antiquity. Furthermore, ancient sources generally inform us of results rather than of experimental technique and procedure.[19] That is one reason why the *literary record* of the experimental activity of the past is no safe guide to the actual extent of that activity. Again, technological advances bespeak a constant activity in experimentation, an activity which for various reasons did not find its way into the literary record. In this we may see a difference between the modes of disseminating scientific information in ancient and in modern times, but not a generic difference between ancient and modern science, as such.

The fact that those Greek scientists of the early period of whom literary records are preserved were also philosophers and the fact that over a long period of time the most influential figure in Greek science was Aristotle[20] have combined at times to give the impres-

18 For examples of experiment in Galen see pages 884-886 of the work of Brunet and Mieli cited in note 1, above. Of particular interest are experiments involving the vivisection of animals, e.g., those experiments in which the spinal cord is cut into at various levels, and the particular type of paralysis resulting from severance at a particular level is noted.

19 See Charles Singer, Greek Science and Modern Science—A Comparison and a Contrast, 16-20 (London, University of London Press, 1920).

20 The great importance of Aristotle should not be permitted to obscure contrary currents such as the development of atomistic viewpoints in mechanics and medicine (see note 15, above) and criticism of Aristotelian dynamical theory, e.g., in the school represented in later times by Philoponus. This is, of course, apart from a general tendency toward empiricism and scepticism, a tendency which was manifested in greater or lesser degree in various periods of Greek science and philosophy as it has been in modern times. Such tendencies are usually corrective reactions against an excessive

sion that Greek science was philosophical rather than scientific. That one and the same person may have devoted thought to both scientific and philosophic questions should not, however, prevent us from appraising his contribution in each field, any more than the presence of superstitious elements in an ancient scientist should be permitted to obscure his really scientific work. Lynn Thorndike in the first volume of his well-known work, A History of Magic and Experimental Science, emphasizes magical and mystical features in certain Greek and Roman scientists to the neglect of the scientific element in their work. But the distinction in aim and spirit between magic and science cannot be too strongly emphasized. It should be remembered, furthermore, that science in its quest for more and more comprehensive viewpoints, a quest to which I have made reference, often finds itself at the borders of philosophy. And the borders are ill-defined precisely because it cannot always be foretold what will prove capable of verification or falsification and what will not. In any case science can never be completely divorced from philosophy whether the latter serves merely to interpret the propositions of science or to criticize its reasoning and abstractions, or to formulate theories of knowledge and reality upon which a system of science must be based.

Indeed, great as is the achievement of Greek science in its second great period, the Hellenistic, with its specialists in mathematics, physics, astronomy, medicine, biology, and geodesy, it may reasonably be held that it was precisely in the union of science and philosophy in the earlier period that Greece made a more significant contribution to the future. It is from this period that we have our first record of sustained and penetrating thought on questions that in one form or another have continued to engage men's minds. I have already referred to some of these basic questions. It is of particular interest to consider this matter at present when the relation between science and philosophy is more intimate than it has been for a long period, a rapprochement necessitated by the funda-

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tendency in the other direction. In fact Aristotle himself represents, in a sense, a reaction toward empiricism from the tendencies of Platonic science.

mental questions raised in connection with relativity theory, new viewpoints in atomic physics, and the basic principles of biological science.

I need but mention at this time, in connection with Greek scientific achievement, the notion of the basic unity of nature, the idea of element in the theory of matter, the elaboration of the atomic hypothesis, the penetrating attempts to understand the nature of chemical change, the abstraction of the notion of force, the steps toward principles of conservation and least action, the concept of organism in biology, the beginnings of a theory of evolution.[21] Thought on basic scientific questions such as these leads naturally to thought on more general philosophic questions culminating in the problems of universals, of causality, of God.

The achievement, then, of the Greek mind at the various levels of scientific activity is a rich achievement both in substance, and in what is even more important in the history of civilization, in spirit and method. It is unnecessary to enter into the question as to whether the achievement of the Greeks in non-scientific activities,

[21] With respect to all these items source material abounds. I have also found the works of Émile Meyerson, especially his Identité et Réalité, very valuable in tracing the development of scientific ideas like atomism, inertia, conservation of matter, etc., from ancient to modern times.

In connection with the theory of chemical change the development of two schools, that which goes back to Aristotle's De Generatione et Corruptione and that which goes back to the ancient atomists is traced by P. Duhem, Le Mixte et la Combinaison Chimique (Paris, Naud, 1902). Note also the literature referred to in Chapter 7 of the work of Brunet and Mieli cited in note 1, above.

With respect to the principle of conservation of weight see note 17, above, and compare Lucian, Demonax 39. In connection with the conservation of effort and the principle of least action see 156.6 of the work cited in note 7, above.

Very instructive are analogies between ancient and modern theories of elements, e.g., in the matter of differentiation by shape (compare ancient atomic theories as well as the rôle played in antiquity by the five regular polyhedra with modern atomic models) and of transmutation (compare ancient theories with modern results in connection with radioactivity and the bombardment of atomic nuclei).

The modern controversy as to determinism and indeterminism in physics (a controversy now raised in connection with quantum theory) may be compared to a similar controversy in ancient atomism (note the function of the Epicurean *clinamen*).

in art and literature, is more significant. It will suffice here to point out that certain qualities of the Greek mind, its innate curiosity, its aesthetic bent, love of order, rationalism, and so forth, reveal themselves in both spheres of activity. But since it is the scientific achievement of the Greeks that has been more often forgotten, it is well to call special attention to it now. Classical students have in the past been criticized for not paying sufficient attention to this achievement. But scientists were at least equally to blame because for so long they taught science as if it began in the sixteenth century or even in the nineteenth century. In recent years, however, both among classicists and among scientists there has been not only a somewhat more sympathetic appreciation of Greek science but a growing feeling that the scientific spirit is in no sense opposed to the classical spirit, and in no sense opposed to the truly humanistic spirit. Be that as it may, the classicist ought to be able, it seems to me, to appreciate Greek science without losing any of his love for Greek art and literature, and the scientist ought to be able to do the same without losing any of his profound admiration for the modern kingdom of science.

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Medieval Science

Pierre Duhem

MEDIEVAL PHYSICS*

A GLANCE AT ANCIENT PHYSICS

Although at the time of Christ's birth Hellenic science had produced nearly all its masterpieces, it was still to give to the world Ptolemy's astronomy, the way for which had been paved for more than a century by the works of Hipparchus. The revelations of Greek thought on the nature of the exterior world ended with the "Almagest," which appeared about A.D. 145, and then began the decline of ancient learning. Those of its works that escaped the fires kindled by Mohammedan warriors were subjected to the barren interpretations of Mussulman commentators and, like parched seed, awaited the time when Latin Christianity would furnish a favourable soil in which they could once more flourish and bring forth fruit. Hence it is that the time when Ptolemy put the finishing touches to his "Great Mathematical Syntax of Astronomy" seems the most opportune in which to study the field of ancient physics. An impassable frontier separated this field into two regions in which different laws prevailed. From the moon's orbit to the sphere enclosing the world, extended the region of beings exempt from generation, change, and death, of perfect, divine beings,

* Reprinted from "Physics, History of," *Catholic Encyclopedia,* XII (1911), pp. 47-52, with the permission of The Catholic University of America Press.

and these were the star-sphere and the stars themselves. Inside the lunar orbit lay the region of generation and corruption, where the four elements and the mixed bodies generated by their mutual combinations were subject to perpetual change.

The science of the stars was dominated by a principle formulated by Plato and the Pythagoreans, according to which all the phenomena presented to us by the heavenly bodies must be accounted for by combinations of circular and uniform motions. Moreover, Plato declared that these circular motions were reducible to the rotation of solid globes all limited by spherical surfaces concentric with the World and the Earth, and some of these homocentric spheres carried fixed or wandering stars. Eudoxus of Cnidus, Calippus, and Aristotle vied with one another in striving to advance this theory of homocentric spheres, its fundamental hypothesis being incorporated in Aristotle's "Physics" and "Metaphysics." However, the astronomy of homocentric spheres could not explain all celestial phenomena, a considerable number of which showed that the wandering stars did not always remain at an equal distance from the Earth. Heraclides Ponticus in Plato's time, and Aristarchus of Samos about 280 B.C. endeavoured to account for all astronomical phenomena by a heliocentric system, which was an outline of the Copernican mechanics; but the arguments of physics and the precepts of theology proclaiming the Earth's immobility, readily obtained the ascendancy over this doctrine which existed in a mere outline. Then the labours of Apollonius Pergæus (at Alexandria, 205 B.C.), of Hipparchus (who made observation at Rhodes in 128 and 127 B.C.), and finally of Ptolemy (Claudius Ptolemæus of Pelusium) constituted a new astronomical system that claimed the Earth to be immovable in the centre of the universe; a system that seemed, as it were, to reach its completion when, between A.D. 142 and 146, Ptolemy wrote a work called "Μεγάλη μαθηματικὴ σύνταξις τῆς ἀστρονομίας," its Arabian title being transliterated by the Christians of the Middle Ages, who named it "Almagest." The astronomy of the "Almagest" explained all astronomical phenomena with a precision which for a long

time seemed satisfactory, accounting for them by combinations of circular motions; but, of the circles described, some were eccentric to the World, whilst others were epicyclic circles, the centres of which described deferent circles concentric with or eccentric to the World; moreover, the motion on the deferent was no longer uniform, seeming so only when viewed from the centre of the equant. Briefly, in order to construct a kinematical arrangement by means of which phenomena could be accurately represented, the astronomers whose work Ptolemy completed had to set at naught the properties ascribed to the celestial substance by Aristotle's "Physics," and between this "Physics" and the astronomy of eccentrics and epicycles there ensued a violent struggle which lasted until the middle of the sixteenth century.

In Ptolemy's time the physics of celestial motion was far more advanced than the physics of sublunary bodies, as, in this science of beings subject to generation and corruption, only two chapters had reached any degree of perfection, namely, those on optics (called perspective) and statics. The law of reflection was known as early as the time of Euclid, about 320 B.C., and to this geometrician was attributed, although probably erroneously, a "Treatise on Mirrors," in which the principles of catoptrics were correctly set forth. Dioptrics, being more difficult, was developed less rapidly. Ptolemy already knew that the angle of refraction is not proportional to the angle of incidence, and in order to determine the ratio between the two he undertook experiments the results of which were remarkably exact.

Statics reached a fuller development than optics. The "Mechanical Questions" ascribed to Aristotle were a first attempt to organize that science, and they contained a kind of outline of the principle of virtual velocities, destined to justify the law of the equilibrium of the lever; besides, they embodied the happy idea of referring to the lever theory the theory of all simple machines. An elaboration, in which Euclid seems to have had some part, brought statics to the stage of development in which it was found by Archimedes (about 287-212 B.C.), who was to raise it to a still

higher degree of perfection. It will here suffice to mention the works of genius in which the great Syracusan treated the equilibrium of the weights suspended from the two arms of a lever, the search for the centre of gravity, and the equilibrium of liquids and floating bodies. The treatises of Archimedes were too scholarly to be widely read by the mechanicians who succeeded this geometrician; these men preferred easier and more practical writings as, for instance, those on the lines of Aristotle's "Mechanical Questions." Various treatises by Heron of Alexandria have preserved for us the type of these decadent works.

SCIENCE AND EARLY CHRISTIAN SCHOLARS

Shortly after the death of Ptolemy, Christian science took root at Alexandria with Origen (about 180-253), and a fragment of his "Commentaries on Genesis," preserved by Eusebius, shows us that the author was familiar with the latest astronomical discoveries, especially the precession of the equinoxes. However, the writings in which the Fathers of the Church comment upon the work of the six days of Creation, notably the commentaries of St. Basil and St. Ambrose, borrow but little from Hellenic physics; in fact, their tone would seem to indicate distrust in the teachings of Greek science, this distrust being engendered by two prejudices: in the first place, astronomy was becoming more and more the slave of astrology, the superstitions of which the Church diligently combatted; in the second place, between the essential propositions of peripatetic physics and what we believe to be the teaching of Holy Writ, contradictions appeared; thus Genesis was thought to teach the presence of water above the heaven of the fixed stars (the firmament) and this was incompatible with the Aristotelean theory concerning the natural place of the elements. The debates raised by this question gave St. Augustine an opportunity to lay down wise exegetical rules, and he recommended Christians not to put forth lightly, as articles of faith, propositions contradicted by physical

science based upon careful experiments. St. Isidore of Seville (d. 636), a bishop, considered it legitimate for Christians to desire to know the teachings of profane science, and he laboured to satisfy this curiosity. His "Etymologies" and "De natura rerum" are merely compilations of fragments borrowed from all the pagan and Christian authors with whom he was acquainted. In the height of the Latin Middle Ages these works served as models for numerous encyclopædias, of which the "De natura rerum" by Bede (about 672-735) and the "De universo" by Rabanus Maurus (776-856) were the best known.

However, the sources from which the Christians of the West imbibed a knowledge of ancient physics became daily more numerous, and to Pliny the Elder's "Natural History," read by Bede, were added Chalcidius's commentary on Plato's "Timæus" and Martianus Capella's "De Nuptiis Philologiæ et Mercurii," these different works inspiring the physics of John Scotus Eriugena. Prior to A.D. 1000 a new Platonic work by Macrobius, a commentary on the "Somnium Scipionis," was in great favour in the schools. Influenced by the various treatises already mentioned, Guillaume of Conches (1080-1150 or 1154) and the unknown author of "De mundi constitutione liber," which, by the way, has been falsely attributed to Bede, set forth a planetary theory making Venus and Mercury satellites of the sun, but Eriugena went still further and made the sun also the centre of the orbits of Mars and Jupiter. Had he but extended this hypothesis to Saturn, he would have merited the title of precursor of Tycho Brahe.

A GLANCE AT ARABIAN PHYSICS

The authors of whom we have heretofore spoken had only been acquainted with Greek science through the medium of Latin tradition, but the time came when it was to be much more completely revealed to the Christians of the West through the medium of Mussulman tradition.

There is no Arabian science. The wise men of Mohammedanism were always the more or less faithful disciples of the Greeks, but were themselves destitute of all originality. For instance, they compiled many abridgments of Ptolemy's "Almagest," made numerous observations, and constructed a great many astronomical tables, but added nothing essential to the theories of astronomical motion; their only innovation in this respect, and, by the way, quite an unfortunate one, was the doctrine of the oscillatory motion of the equinoctial points, which the Middle Ages ascribed to Thâbit ibn Kûrrah (836-901), but which was probably the idea of Al-Zarkali, who lived much later and made observations between 1060 and 1080. This motion was merely the adaptation of a mechanism conceived by Ptolemy for a totally different purpose.

In physics, Arabian scholars confined themselves to commentaries on the statements of Aristotle, their attitude being at times one of absolute servility. This intellectual servility to Peripatetic teaching reached its climax in Abul ibn Roshd, whom Latin scholastics called Averroës (about 1120-98) and who said: Aristotle "founded and completed logic, physics, and metaphysics . . . because none of those who have followed him up to our time, that is to say, for four hundred years, have been able to add anything to his writings or to detect therein an error of any importance." This unbounded respect for Aristotle's work impelled a great many Arabian philosophers to attack Ptolemy's "Astronomy" in the name of Peripatetic physics. The conflict between the hypotheses of eccentrics and epicycles was inaugurated by Ibn Bâdja, known to the scholastics as Avempace (d. 1138), and Abu Bekr ibn el-Tofeil, called Abubacer by the scholastics (d. 1185), and was vigorously conducted by Averroës, the protégé of Abubacer. Abu Ishâk ibn al-Bitrogi, known by the scholastics as Alpetragius, another disciple of Abubacer and a contemporary of Averroës, advanced a theory on planetary motion wherein he wished to account for the phenomena peculiar to the wandering stars, by compounding rotations of homocentric spheres; his treatise, which was more neo-Platonic than Peripatetic, seemed to be a Greek book altered,

or else a simple plagiarism. Less inflexible in his Peripateticism than Averroës and Alpetragius, Moses ben Maimun, called Maimonides (1139-1204), accepted Ptolemy's astronomy despite its incompatibility with Aristotelean physics, although he regarded Aristotle's sublunary physics as absolutely true.

ARABIAN TRADITION AND LATIN SCHOLASTICISM

It cannot be said exactly when the first translations of Arabic writings began to be received by the Christians of the West, but it was certainly previously to the time of Gerbert (Sylvester II; about 930-1003). Gerbert used treatises translated from the Arabic, and containing instructions on the use of astronomical instruments, notably the astrolabe, to which instrument Hermann the Lame (1013-54) devoted part of his researches. In the beginning of the twelfth century the contributions of Mohammedan science and philosophy to Latin Christendom became more and more frequent and important. About 1120 or 1130 Adelard of Bath translated the "Elements" of Euclid, and various astronomical treatises; in 1141 Peter the Venerable, Abbot of Cluny, found two translators, Hermann the Second (or the Dalmatian) and Robert of Rétines, established in Spain; he engaged them to translate the Koran into Latin, and in 1143 these same translators made Christendom acquainted with Ptolemy's planisphere. Under the direction of Raimond (Archbishop of Toledo, 1130; d. 1150), Domengo Gondisalvi (Gonsalvi; Gundissalinus), Archdeacon of Segovia, began to collaborate with the converted Jew, John of Luna, erroneously called John of Seville (Johannes Hispalensis). While John of Luna applied himself to works in mathematics, he also assisted Gondisalvi in translating into Latin a part of Aristotle's physics, the "De Cælo" and the "Metaphysics," besides treatises by Avicenna, Al-Gazâli, Al-Fârâbi, and perhaps Salomon ibn Gebirol (Avicebron). About 1134 John of Luna translated Al-Fergâni's treatise "Astronomy," which was an abridgement of the "Almagest,"

thereby introducing Christians to the Ptolemaic system, while at the same time his translations, made in collaboration with Gondisalvi, familiarized the Latins with the physical and metaphysical doctrines of Aristotle. Indeed the influence of Aristotle's "Physics" was already apparent in the writings of the most celebrated masters of the school of Chartres (from 1121 until before 1155), and of Gilbert de la Porrée (1070-1154).

The abridgement of Al-Fergâni's "Astronomy," translated by John of Luna, does not seem to have been the first work in which the Latins were enabled to read the exposition of Ptolemy's system; it was undoubtedly preceded by a more complete treatise, the "De Scientia stellarum" of Albategnius (Al-Battâni), latinized by Plato of Tivoli about 1120. However, the "Almagest" itself was still unknown. Moved by a desire to read and translate Ptolemy's immortal work, Gerard of Cremona (d. 1187) left Italy and went to Toledo, eventually making the translation which he finished in 1175. Besides the "Almagest," Gerard rendered into Latin other works, of which we have a list comprising seventy-four different treatises. Some of these were writings of Greek origin, and included a large portion of the works of Aristotle, a treatise by Archimedes, Euclid's "Elements" (completed by Hypsicles), and books by Hippocrates. Others were Arabic writings, such as the celebrated "Book of Three Brothers," composed by the Beni Mûsa, "Optics" by Ibn Al-Haitam (the Alhazen of the Scholastics), "Astronomy" by Geber, and "De motu octavæ sphæræ" by Thâbit ibn Kûrrah. Moreover, in order to spread the study of Ptolemaic astronomy, Gerard composed at Toledo his "Theoricæ planetarum," which during the Middle Ages became one of the classics of astronomical instruction. Beginners who obtained their first cosmographic information through the study of the "Sphæra," written about 1230 by Joannes de Sacrobosco, could acquire a knowledge of eccentrics and epicycles by reading the "Theoricæ planetarum" of Gerard of Cremona. In fact, until the sixteenth century, most astronomical treatises assumed the form of commentaries, either on the "Sphæra," or the "Theoricæ planetarum."

"Aristotle's philosophy," wrote Roger Bacon in 1267, "reached a great development among the Latins when Michael Scot appeared about 1230, bringing with him certain parts of the mathematical and physical treatises of Aristotle and his learned commentators." Among the Arabic writings made known to Christians by Michael Scot (before 1291; astrologer to Frederick II) were the treatises of Aristotle and the "Theory of Planets," which Alpetragius had composed in accordance with the hypothesis of homocentric spheres. The translation of this last work was completed in 1217. By propagating among the Latins the commentaries on Averroës and on Alpetragius's theory of the planets, as well as a knowledge of the treatises of Aristotle, Michael Scot developed in them an intellectual disposition which might be termed Averroism, and which consisted in a superstitious respect for the word of Aristotle and his commentator.

There was a metaphysical Averroism which, because professing the doctrine of the substantial unity of all human intellects, was in open conflict with Christian orthodoxy; but there was likewise a physical Averroism which, in its blind confidence in Peripatetic physics, held as absolutely certain all that the latter taught on the subject of the celestial substance, rejecting in particular the system of epicycles and eccentrics in order to commend Alpetragius's astronomy of homocentric spheres.

Scientific Averroism found partisans even among those whose purity of faith constrained them to struggle against metaphysical Averroism, and who were very often Peripatetics in so far as was possible without formally contradicting the teaching of the Church. For instance, William of Auvergne (d. 1249), who was the first to combat "Aristotle and his sectarians" on metaphysical grounds, was somewhat misled by Alpetragius's astronomy, which, moreover, he understood but imperfectly. Albertus Magnus (1193 or 1205-1280) followed to a great extent the doctrine of Ptolemy, although he was sometimes influenced by the objections of Averroës or affected by Alpetragius's principles. Vincent of Beauvais in his "Speculum quadruplex," a vast encyclopædic compilation pub-

lished about 1250, seemed to attach great importance to the system of Alpetragius, borrowing the exposition of it from Albertus Magnus. Finally, even St. Thomas Aquinas gave evidence of being extremely perplexed by the theory (1227-74) of eccentrics and epicycles which justified celestial phenomena by contradicting the principles of Peripatetic physics, and the theory of Alpetragius which honoured these principles but did not go so far as to represent their phenomena in detail.

This hesitation, so marked in the Dominican school, was hardly less remarkable in the Franciscan, Robert Grosseteste or Greathead (1175-1253), whose influence on Franciscan studies was so great, followed the Ptolemaic system in his astronomical writings, his physics being imbued with Alpetragius's ideas. St. Bonaventure (1221-74) wavered between doctrines which he did not thoroughly understand, and Roger Bacon (1214-92) in several of his writings weighed with great care the arguments that could be made to count for or against each of these two astronomical theories, without eventually making a choice. Bacon, however, was familiar with a method of figuration in the system of eccentrics and epicycles which Alhazen had derived from the Greeks; and in this figuration all the motions acknowledged by Ptolemy were traced back to the rotation of solid orbs accurately fitted one into the other. This representation, which refuted most of the objections raised by Averroës against Ptolemaic astronomy, contributed largely to propagate the knowledge of this astronomy, and it seems that the first of the Latins to adopt it and expatiate on its merits was the Franciscan Bernard of Verdun (end of thirteenth century), who had read Bacon's writings. In sublunary physics the authors whom we have just mentioned did not show the hesitation that rendered astronomical doctrines so perplexing, but on almost all points adhered closely to Peripatetic opinions.

THE SCIENCE OF OBSERVATION AND ITS PROGRESS—ASTRONOMERS —THE STATICS OF JORDANUS—THIERRY OF FREIBERG—PIERRE OF MARICOURT

Averroism had rendered scientific progress impossible, but fortunately in Latin Christendom it was to meet with two powerful enemies: the unhampered curiosity of human reason, and the authority of the Church. Encouraged by the certainty resulting from experiments, astronomers rudely shook off the yoke which Peripatetic physics had imposed upon them. The School of Paris in particular was remarkable for its critical views and its freedom of attitude towards the argument of authority. In 1290 William of Saint-Cloud determined with wonderful accuracy the obliquity of the ecliptic and the time of the vernal equinox, and his observations led him to recognize the inaccuracies that marred the "Tables of Toledo," drawn up by Al-Zarkali. The theory of the precession of the equinoxes, conceived by the astronomers of Alfonso X of Castile, and the "Alphonsine Tables" set up in accordance with this theory, gave rise in the first half of the fourteenth century to the observations, calculations, and critical discussions of Parisian astronomers, especially of Jean des Linières and his pupil John of Saxonia or Connaught.

At the end of the thirteenth century and the beginning of the fourteenth, sublunary physics owed great advancement to the simultaneous efforts of geometricians and experimenters—their method and discoveries being duly boasted of by Roger Bacon who, however, took no important part in their labours. Jordanus de Nemore, a talented mathematician who, not later than about the beginning of the thirteenth century, wrote treatises on arithmetic and geometry, left a very short treatise on statics in which, side by side with erroneous propositions, we find the law of the equilibrium of the straight lever very correctly established with the aid of the principle of virtual displacements. The treatise, "De ponderibus," by Jor-

danus provoked research on the part of various commentators, and one of these, whose name is unknown and who must have written before the end of the thirteenth century, drew, from the same principle of virtual displacements, demonstrations, admirable in exactness and elegance, of the law of the equilibrium of the bent lever, and of the apparent weight (*gravitas secundum situm*) of a body on an inclined plane.

Alhazen's "Treatise on Perspective" was read thoroughly by Roger Bacon and his contemporaries, John Peckham (1228-91), the English Franciscan, giving a summary of it. About 1270 Witelo (or Witek; the *Thuringopolonus*), composed an exhaustive ten-volume treatise on optics, which remained a classic until the time of Kepler, who wrote a commentary on it.

Albertus Magnus, Roger Bacon, John Peckham, and Witelo were deeply interested in the theory of the rainbow, and, like the ancient meteorologists, they all took the rainbow to be the image of the sun reflected in a sort of a concave mirror formed by a cloud resolved into rain. In 1300 Thierry of Freiberg proved by means of carefully conducted experiments in which he used glass balls filled with water, that the rays which render the bow visible have been reflected on the inside of the spherical drops of water, and he traced with great accuracy the course of the rays which produce the rainbows respectively.

The system of Thierry of Freiberg, at least that part relating to the primary rainbow, was reproduced about 1360 by Themon, "Son of the Jew" (*Themo ju dæi*), and, from his commentary on "Meteors," it passed on down to the days of the Renaissance when, having been somewhat distorted, it reappeared in the writings of Alessandro Piccolomini, Simon Porta, and Marco and Antonio de Dominis, being thus propagated until the time of Descartes.

The study of the magnet had also made great progress in the course of the thirteenth century; the permanent magnetization of iron, the properties of the magnetic poles, the direction of the Earth's action exerted on these poles or of their action on one another, are all found very accurately described in a treatise written

in 1269 by Pierre of Maricourt (Petrus Peregrinus). Like the work of Thierry of Freiberg on the rainbow, the "Epistola de magnete" by Maricourt was a model of the art of logical sequence between experiment and deduction.

THE ARTICLES OF PARIS (1277)—POSSIBILITY OF VACUUM

The University of Paris was very uneasy because of the antagonism existing between Christian dogmas and certain Peripatetic doctrines, and on several occasions it combatted Aristotelean influence. In 1277 Etienne Tempier, Bishop of Paris, acting on the advice of the theologians of the Sorbonne, condemned a great number of errors, some of which emanated from the astrology, and others from the philosophy of the Peripatetics. Among these errors considered dangerous to faith were several which might have impeded the progress of physical science, and hence it was that the theologians of Paris declared erroneous the opinion maintaining that God Himself could not give the entire universe a rectilinear motion, as the universe would then leave a vacuum behind it, and also declared false the notion that God could not create several worlds. These condemnations destroyed certain essential foundations of Peripatetic physics; because, although, in Aristotle's system, such propositions were ridiculously untenable, belief in Divine Omnipotence sanctioned them as possible, whilst waiting for science to confirm them as true. For instance, Aristotle's physics treated the existence of an empty space as a pure absurdity; in virtue of the "Articles of Paris" Richard of Middletown (about 1280) and, after him, many masters at Paris and Oxford admitted that the laws of nature are certainly opposed to the production of empty space, but that the realization of such a space is not, in itself, contrary to reason; thus, without any absurdity, one could argue on vacuum and on motion in a vacuum. Next, in order that such arguments might be legitimatized, it was necessary to create that branch of mechanical science known as dynamics.

THE EARTH'S MOTION—ORESME

The "Articles of Paris" were of about the same value in supporting the question of the Earth's motion as in furthering the progress of dynamics by regarding vacuum as something conceivable.

Aristotle maintained that the first heaven (the firmament) moved with a uniform rotary motion, and that the Earth was absolutely stationary, and as these two propositions necessarily resulted from the first principles relative to time and place, it would have been absurd to deny them. However, by declaring that God could endow the World with a rectilinear motion, the theologians of the Sorbonne acknowledged that these two Aristotelean propositions could not be imposed as a logical necessity and thenceforth, whilst continuing to admit that, as a fact, the Earth was immovable and that the heavens moved with a rotary diurnal motion, Richard of Middletown and Duns Scotus (about 1275-1308) began to formulate hypotheses to the effect that these bodies were animated by other motions, and the entire school of Paris adopted the same opinion. Soon, however, the Earth's motion was taught in the School of Paris, not as a possibility, but as a reality. In fact, in the specific setting forth of certain information given by Aristotle and Simplicius, a principle was formulated which for three centuries was to play a great rôle in statics, viz. that every heavy body tends to unite its centre of gravity with the centre of the Earth.

When writing his "Questions" on Aristotle's "De Cælo" in 1368, Albert of Helmstadt (or of Saxony) admitted this principle, which he applied to the entire mass of the terrestrial element. The centre of gravity of this mass is constantly inclined to place itself in the centre of the universe, but, within the terrestrial mass, the position of the centre of gravity is incessantly changing. The principal cause of this variation is the erosion brought about by the streams and rivers that continually wear away the land surface, deepening its valleys and carrying off all loose matter to the bed of the sea, thereby producing

a displacement of weight which entails a ceaseless change in the position of the centre of gravity. Now, in order to replace this centre of gravity in the centre of the universe, the Earth moves without ceasing; and meanwhile a slow but perpetual exchange is being effected between the continents and the oceans. Albert of Saxony ventured so far as to think that these small and incessant motions of the Earth could explain the phenomena of the precession of the equinoxes. The same author declared that one of his masters, whose name he did not disclose, announced himself in favour of the daily rotation of the Earth, inasmuch as he refuted the arguments that were opposed to this motion. This anonymous master had a thoroughly convinced disciple in Nicole Oresme who, in 1377 being then Canon of Rouen and later Bishop of Lisieux, wrote a French commentary on Aristotle's treatise "De Cælo," maintaining with quite as much force as clearness that neither experiment nor argument could determine whether the daily motion belonged to the firmament of the fixed stars or to the Earth. He also showed how to interpret the difficulties encountered in "the Sacred Scriptures wherein it is stated that the sun turns, etc. It might be supposed that here Holy Writ adapts itself to the common mode of human speech, as also in several places, for instance, where it is written that God repented Himself, and was angry and calmed Himself and so on, all of which is, however, not to be taken in a strictly literal sense." Finally, Oresme offered several considerations favourable to the hypothesis of the Earth's daily motion. In order to refute one of the objections raised by the Peripatetics against this point, Oresme was led to explain how, in spite of this motion, heavy bodies seemed to fall in a vertical line; he admitted their real motion to be composed of a fall in a vertical line and a diurnal rotation identical with that which they would have if bound to the Earth. This is precisely the principle to which Galileo was afterwards to turn.

PLURALITY OF WORLDS

Aristotle maintained the simultaneous existence of several worlds to be an absurdity, his principal argument being drawn from his theory of gravity, whence he concluded that two distinct worlds could not coexist and be each surrounded by its elements; therefore it would be ridiculous to compare each of the planets to an earth similar to ours. In 1277 the theologians of Paris condemned this doctrine as a denial of the creative omnipotence of God; Richard of Middletown and Henry of Ghent (who wrote about 1280), Guillaume Varon (who wrote a commentary on the "Sentences" about 1300), and, towards 1320, Jean de Bassols, William of Occam (d. after 1347), and Walter Burley (d. about 1343) did not hesitate to declare that God could create other worlds similar to ours. This doctrine, adopted by several Parisian masters, exacted that the theory of gravity and natural place developed by Aristotle be thoroughly changed; in fact, the following theory was substituted for it. If some part of the elements forming a world be detached from it and driven far away, its tendency will be to move towards the world to which it belongs and from which it was separated; the elements of each world are inclined so to arrange themselves that the heaviest will be in the centre and the lightest on the surface. This theory of gravity appeared in the writings of Jean Buridan of Béthune, who became rector of the University of Paris in 1327, teaching at that institution until about 1360; and in 1377 this same theory was formally proposed by Oresme. It was also destined to be adopted by Copernicus and his first followers, and to be maintained by Galileo, William Gilbert, and Otto von Guericke.

DYNAMICS—THEORY OF IMPETUS—INERTIA—CELESTIAL AND SUBLUNARY MECHANICS IDENTICAL

If the School of Paris completely transformed the Peripatetic theory of gravity, it was equally responsible for the overthrow of Aristotelean dynamics. Convinced that, in all motion, the mover should be directly contiguous to the body moved, Aristotle had proposed a strange theory of the motion of projectiles. He held that the projectile was moved by the fluid medium, whether air or water, through which it passed and this, by virtue of the vibration brought about in the fluid at the moment of throwing, and spread through it. In the sixth century of our era this explanation was strenuously opposed by the Christian Stoic, Joannes Philoponus, according to whom the projectile was moved by a certain power communicated to it at the instant of throwing; however, despite the objections raised by Philoponus, Aristotle's various commentators, particularly Averroës, continued to attribute the motion of the projectile to the disturbance of the air, and Albertus Magnus, St. Thomas Aquinas, Roger Bacon, Gilles of Rome, and Walter Burley persevered in maintaining this error. By means of most spirited argumentation, William of Occam made known the complete absurdity of the Peripatetic theory of the motion of projectiles. Going back to Philoponus's thesis, Buridan gave the name *impetus* to the virtue or power communicated to the projectile by the hand or instrument throwing it; he declared that in any given body in motion, this impetus was proportional to the velocity, and that, in different bodies in motion propelled by the same velocity, the quantities of impetus were proportional to the mass or quantity of matter defined as it was afterwards defined by Newton.

In a projectile, impetus is gradually destroyed by the resistance of air or other medium and is also destroyed by the natural gravity of the body in motion, which gravity is opposed to the impetus if the projectile be thrown upward; this struggle explains the different

peculiarities of the motion of projectiles. In a falling body, gravity comes to the assistance of impetus which it increases at every instant, hence the velocity of the fall is increasing incessantly.

With the assistance of these principles concerning impetus, Buridan accounts for the swinging of the pendulum. He likewise analyses the mechanism of impact and rebound and, in this connexion, puts forth very correct views on the deformations and elastic reactions that arise in the contiguous parts of two bodies coming into collision. Nearly all this doctrine of impetus is transformed into a very correct mechanical theory if one is careful to substitute the expression *vis viva* for impetus. The dynamics expounded by Buridan were adopted in their entirety by Albert of Saxony, Oresme, Marsile of Inghem, and the entire School of Paris. Albert of Saxony appended thereto the statement that the velocity of a falling body must be proportional either to the time elapsed from the beginning of the fall or to the distance traversed during this time. In a projectile, the impetus is gradually destroyed either by the resistance of the medium or by the contrary tendency of the gravity natural to the body. Where these causes of destruction do not exist, the impetus remains perpetually the same, as in the case of a millstone exactly centred and not rubbing on its axis; once set in motion it will turn indefinitely with the same swiftness. It was under this form that the law of inertia at first became evident to Buridan and Albert of Saxony.

The conditions manifested in this hypothetic millstone are realized in the celestial orbs, as in these neither friction nor gravity impedes motion; hence it may be admitted that each celestial orb moves indefinitely by virtue of a suitable impetus communicated to it by God at the moment of creation. It is useless to imitate Aristotle and his commentators by attributing the motion of each orb to a presiding spirit. This was the opinion proposed by Buridan and adopted by Albert of Saxony; and whilst formulating a doctrine from which modern dynamics was to spring, these masters understood that the same dynamics governs both celestial and sublunary bodies. Such an idea was directly opposed to the essential

distinction established by ancient physics between these two kinds of bodies. Moreover, following William of Occam, the masters of Paris rejected this distinction; they acknowledged that the matter constituting celestial bodies was of the same nature as that constituting sublunary bodies and that, if the former remained perpetually the same, it was not because they were, by nature, incapable of change and destruction, but simply because the place in which they were contained no agent capable of corrupting them. A century elapsed between the condemnations pronounced by Etienne Tempier (1277) and the editing of the "Traité du Ciel et du Monde" by Oresme (1377) and, within that time, all the essential principles of Aristotle's physics were undermined, and the great controlling ideas of modern science formulated. This revolution was mainly the work of Oxford Franciscans like Richard of Middletown, Duns Scotus, and William of Occam, and of masters in the School of Paris, heirs to the tradition inaugurated by these Franciscans; among the Parisian masters Buridan, Albert of Saxony, and Oresme were in the foremost rank.

E. J. Holmyard

CHEMISTRY IN ISLAM*

The standard histories of chemistry devote very little space to the rise and progress of chemistry in Islâm, and the scanty information which they give is very largely erroneous or misleading. This is no fault of their authors, who have done the best they could with material that is seriously inadequate. Fortunately, Arab chemistry is now receiving much more attention, although, when the scholars who are devoting themselves to this branch of learning may be numbered on the fingers of one hand, the time is still far distant when it will be possible to gauge properly the services of Muslim workers to the young science. It is, however, not impossible even now to gain a rough idea of these services, and to draw attention to some of the more serious errors which have found their way into general circulation.

The main tendency of modern research has been to show that the reputation as chemists which the early Muslims enjoyed in mediaeval times was to a large extent justified. The temporary eclipse which this reputation suffered in the latter half of the nine-

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teenth century was due in part to Kopp's unfavourable opinion and in part to the over-hasty conclusions which Berthelot drew from a superficial study of a very limited portion of the material accessible for examination. Kopp, whose historical researches have won the admiration of all his successors, was no more an Arabist than was Berthelot, so that it is no disparagement of their labours to say that many of their conclusions upon Arabic chemistry will not stand the test of criticism in the light of the more ample information now available. Perhaps the most insidious of the errors into which these and other historians have been led is the wholesale rejection as spurious of mediaeval Latin treatises on chemistry claiming to be translations from the Arabic. The arguments for rejection have been based almost entirely upon considerations of style. In view, however, of the extreme difference between the structures of the two languages, accentuated in this particular instance by the highly technical modes of expression, it ought, perhaps, to have been obvious—as it certainly is when attention has been directed to it—that to draw far-reaching conclusions from this source alone is a very unsound procedure. A far more reliable criterion than style is content, but a closer investigation of the texts of the works in question will often reveal phrases and terms which are characteristically Arabic, and although it may not be possible in a given instance to point, at the moment, to the Arabic original of a Latin chemical book, the Arabic thought and mode of treatment which permeate it not seldom impress themselves most strongly upon one who knows the writing of the Muslim chemists in their native dress.

It is necessary to remember that many an Arabic chemical treatise was doubtless edited more or less severely by its translator, so that, while admitting the irrefutable fact that falsification and the fathering of spurious books upon illustrious names was by no means uncommon in the Middle Ages, we should at the same time be very cautious in rejecting altogether any book the pseudepigraphical nature of which is not plainly observable. The importance of this canon in the subject under consideration can scarcely

be estimated too highly. One must not, for example, conclude that a book is spurious merely because it appears unlikely that its reputed author would have been interested in alchemy: alchemy flourished in strange places, and an alchemical tract by an Imām or a Ṣûfî would not have appeared strange to contemporaries. In cases of doubt, it is always safer to follow tradition than to reject it upon insufficient grounds, and as this is the course I have adopted in the present sketch I have thought it advisable to explain my reasons at some length.

One of the peculiar difficulties with which the student of alchemy has to contend is the technical language employed by most of the adepts. It is often obscure, not infrequently enigmatical, and occasionally quite incomprehensible. This characteristic is common to alchemical works in all languages, and Arabic is no exception. Scholars, however, who know how far the treatises of mediaeval European alchemists are tainted in this way will be pleasantly surprised when they come to read the early Muslim books. Here it is possible to distinguish clearly two main divisions. On the one hand there is a series of treatises which, rudimentary as is the knowledge they reveal when judged by modern standards, are yet inspired by the true scientific spirit and can be interpreted with comparative ease by a present-day chemist. To this class belong the majority of the books of Jâbir ibn Hayyân and of Rhazes; the sections on chemistry in the *Mafātīḥ al-'Ulûm,* the Letters of the Ikhwân al-Ṣafâ and certain other encyclopaedias; various books of recipes, and so on. On the other hand, there are those treatises which continue the Alexandrian tradition and those which, although couched in alchemical language, are for the most part mystical books, the authors of which use the technical terms of chemistry to express religious or esoteric ideas. With these may be grouped the numerous books on magic, in connection with which it may be remarked that, in spite of the notorious affection shown by Muslims for magical practices, Arabic chemistry is astonishingly little infected with them. It is true that the Muslim chemist often interested himself in magic and occasionally wrote books on the subject, but he

was usually fairly successful in keeping the two "sciences" clear of one another.

In the case of many authors, the distinction between the two divisions described in the last paragraph is not a sharp one, but on the whole less difficulty will be found in deciding whether an Arabic work on alchemy is to be interpreted scientifically or not, than is the case with mediaeval European treatises of a similar nature. One fact, indeed, stands out conspicuously, *viz.*, that two Muslim chemists—one a Persian—were scientists of the first rank, not unworthy to be classed with Boyle, Lavoisier, and Priestley: they were Jâbir and Rhazes, and it is of significance that they both lived in comparatively early days of the Islamic period. Jâbir may be placed about 720-800 A.D., while Rhazes died in 923 or 932. A fairly extensive study of the writings of later authors has served only to strengthen my conviction that the true founder of chemistry as a science was Jâbir ibn Hayyân. Further advance in detail was undoubtedly made by his successors, but, with the exception of Rhazes—who himself derived much of his information from Jâbir's books—there is no Muslim who can be said to have made a contribution *of the first order* to the development of the science. For the most part, they appear to have contented themselves with a repetition of Jâbir's work and with an endless and in general profitless discussion of his theoretical views. There are, of course, exceptions of a minor character, and the Muslims had the inestimable virtue from a scientific point of view of rating practical experience very highly, but it is impossible to name any other Muslim chemist of the calibre of Jâbir and Rhazes. Al-Jildakî, for example, whose chemical writings are preserved in large numbers in our libraries, was scarcely more than a mere compiler, and although his habit of making copious quotations from the books of earlier writers is invaluable in the study of the history of chemistry in Islâm, his experience of laboratory work was clearly extremely limited.

Jâbir himself was a very fluent writer, and a large number of his books are extant. Unfortunately, only a few of them have so far

been published, but I am happy to say that M. Paul Geuthner, the Orientalist publisher of Paris, has recently agreed to publish a complete edition of all those works of Jâbir which exist in manuscript form, and that the first fascicule will probably appear this winter. Until the books have been thoroughly studied, it is, of course, impossible to give any final estimate of Jâbir's attainments in chemistry, but it is very clear that, besides possessing great intellectual capacity, he was also an accomplished experimentalist. Perhaps his most important contribution to the progress of science was his theory that all metals are composed of mercury and sulphur, or rather of two principles to which mercury and sulphur are closely similar. This theory, which is really a remarkably acute one for so early a period, can be traced through succeeding centuries to its final elaboration in the form of the phlogiston theory of Becher and Stahl. It is true that the latter theory long outlived its usefulness and became a formidable obstacle to advance, but in its inception it fulfilled all the tests of a good scientific theory, and it is interesting to be able to trace it back to the days of Hârûn al-Rashîd. On the practical side, Jâbir gives accurate instructions for the preparation of many metals and metallic compounds and for the construction of apparatus. He appears to have been something of a Greek scholar, for he is imbued with Aristotelian ideas and theories although it is almost certain that no translation of Aristotle existed at that time. He gives moreover, for the first time, the text of the Emerald Table of "Hermes," which he claims to have obtained from a work of Apollonius of Tyana and which is possibly of Greek origin.

On the counter reckoning, it is necessary to state that Jâbir had leanings to mysticism and did not always succeed in preventing occult and obscure conceptions from contaminating his science. This is not surprising, in view of the material upon which he must have been educated in the chemical sense; what is surprising is the extent to which he cut himself free from these encumbrances and set chemistry upon firm foundations. His belief in the possibility of transmutation was of course in agreement with the philosophical

atmosphere of the age, and in the absence of reliable methods of chemical analysis early chemists must often have been honestly convinced that they had actually brought transmutation about.

The fascinating problem of whether the Latin works ascribed to Jâbir (Geber) are authentic or not cannot be dealt with here, but attention may be drawn to the fact that Dr. Ernst Darmstaedter of Munich has recently made a discovery of the first importance in this connection. He has, in short, discovered the Latin text of Jâbir's *Book of Mercy* in a manuscript which contains also some of the Latin works in question. This shows us, on the one hand, that Arabic works of Jâbir were actually translated into Latin in the Middle Ages, while the occurrence of the *Summa perfectionis* in the same volume and in the same hand is at least strong presumptive evidence of a possible common origin. Further, although the *Summa* and the related books do not give one the impression of being direct and literal translations from the Arabic, it must be remembered, as has been pointed out above, that the argument from style is very unsound. A comparison of the content of the *Summa* with that of certain of Jâbir's Arabic works leaves a very different impression, and even in the Latin texts there are obvious signs of an Arabic origin to the practised eye.

It should not be thought that the theory of transmutation was universally accepted among Muslim scientists. Sceptics were active in the earliest days, and later on received weighty support from Avicenna. It has usually been denied by European scholars that Avicenna took any interest in alchemy, and all the Latin treatises on the subject ascribed to him have been dismissed as forgeries. In this respect Avicenna has suffered the same treatment as that meted out to Geber, so that it is of particular importance to observe that the authenticity of at least one of the so-called forgeries is definitely established. The tract entitled *De congelatione et conglutinatione lapidum,* printed in some collectaneous treatises on alchemy, and occurring in manuscript in Trinity College, Cambridge, and elsewhere, was rejected by Kopp and has been regarded as spurious. In it, Avicenna explains at some length his reasons

for disbelieving in the possibility of transmutation and also describes his views on the formation of minerals, etc. A careful study of the text of this book led me to the opinion that it was genuine, both because its style was distinctly Arabic and because the attitude adopted by the author to the possibility of transmutation is exactly that ascribed to Avicenna by Al-Jildakî. The latter, in describing the history of alchemy in Islâm, says: "I have seen a book by the *Ra'îs* Ibn Sînâ in which he considers the aims of the sages and their remarks upon alchemy, and denies the truth thereof and maintains the falsity . . . He says that it is not possible to change the essential natures of things, and that silver cannot be changed into gold . . . and likewise with the other metals. But he thought it possible to cause a white dye to enter copper so giving it the appearance and colour of silver, although it would still be merely dyed copper and not silver." In another place, Al-Jildakî mentions that Ibn Sînâ combats the opinions of the alchemists in his book called *Al Shifā'*. An examination of the *Shifā'* proved that Al-Jildakî was, as he usually is in matters of this sort, correct. In point of fact, the relevant passages are to be found in that part of the *Shifā'* which deals with the natural sciences (*fann al-tabî'iât*), and the Latin tract *De congelatione et conglutinatione lapidum* is a close translation of these passages. It will be seen, therefore, that the caution expressed in this article relating to a summary rejection of mediaeval Latin chemical treatises was justified; and the example just given is by no means unique. Unfortunately, success has not yet attended the search for the Arabic texts of the *Summa perfectionis*, etc., but I think it will be admitted, in the light of the facts just described, that the scholars who maintain that these works are spurious will have to adduce far weightier evidence than has been put forward hitherto if they are to be held to have established their case.

On Rhazes (Abu Bakr Muhammad ibn Zakariyya Al-Râzî), the great Persian physician and chemist, we await with impatience the book promised us by Prof. Dr. Julius Ruska of Heidelberg, whose illuminating and scholarly researches upon Muslim chem-

istry it would be an impertinence for me to praise. Rhazes was a very clear thinker, and the high opinion of his attainments in medicine reached by Prof. E. G. Browne, whose comparatively early death is universally lamented, finds its counterpart in the admiration of those who have studied the *Kitâb sirr al-asrâr* and other chemical works. From them it is evident that, while Rhazes believed in the possibility of transmutation, he was far more interested in the application of chemistry to medicine, and his classification of chemicals and instructions for their preparation and purification connote a synthetic mind and a remarkable experimental skill. Rhazes was, in fact, the first of the Iatrochemists, and his services to chemistry may be compared to those of Paracelsus, although no two men could well have differed more in character: Rhazes was modest, kindly, unassuming, generous to the poor, and possessed of all those qualities which go to make up a noble man, while Paracelsus seems to have been what an Englishman would describe as an outsider.

Of the later chemists of Islâm there is little which can profitably be said within the limits of the present article, though it need hardly be remarked that they offer many fascinating problems to the specialist. Perhaps the most elusive figure is that of the author of the celebrated work known as the *Rutbatu'l-Ḥakîm* (The Sage's Step), who was for long considered to be the famous astronomer and mathematician of Muslim Spain, Maslama al-Majrîṭî. From internal evidence, however, it is certain that the *Rutba* must have appeared after Maslama's death in 1007, and the mystery of its author has not been solved. It is universally ascribed to Maslama by the Muslims themselves, and some of its characteristics would agree very well with this ascription, but there are difficulties in accepting it which have proved insuperable. The *Rutba* is in many ways a valuable book, for it throws much light upon scientific thought in Spain in the XIth. century of our era, *i.e.,* just before the great wave of transmission of science from Islâm to Latin Christianity set in. It shows that the great names of Rhazes and Jâbir still held sway after a lapse of nearly two centuries, and so prepares us for

the reputation of these two men among the alchemists of mediaeval Europe. It also bears witness to the fact that as far as theoretical views are concerned there was very little advance in the intervening period, and that the influence of magical practices was increasing. Our knowledge of alchemy in Muslim Spain is unfortunately extremely limited, so that the information which can be gathered from the *Rutba* and other similar works is exceptionally useful.

The task of translation of Arabic chemical treatises into Latin was begun, if tradition is to be trusted, by the Englishman Robert of Chester in the XIIth. century, and was continued by Gerard of Cremona and other well-known mediaeval scholars. The chief centre of activity was, of course, Spain, though the alternative route *via* Sicily and southern Italy was of much importance. The time is not yet ripe for the full story of this transmission; the ground must first be cleared by the study of the development of chemistry in Islâm itself, after which there will be a much better chance of successfully solving the innumerable problems which are presented to us by the course of chemistry in Latin Europe.

No account of chemistry in Islâm would be even approximately complete which omitted to mention Abu'l-Qâsim al-'Irâqî and Aidamir al-Jildakî. The first of these men lived in the XIIIth. century, probably at Cairo, and has left us several books which, apart from their intrinsic interest, serve to indicate the trend of alchemical thought and practice in Islâm after the process of transmission to Europe had been in action for some considerable time. It is very obvious that in Al-'Irâqî's time the reaction of European scientific thought upon Islâm had not yet begun, and the contrast between the two intellectual worlds could not be better exemplified than in the persons of Al-'Irâqî and his contemporary Roger Bacon. The driving force of Islâm was beginning to grow weak, while the new stimulus which Arabic learning had given to Europe had resulted in the scientific renaissance which was to reach its full development a few years later. Al-'Irâqî's outlook is that of his predecessors of three or four centuries earlier and although there

was unquestionably advance in empirical practical chemistry, the theoretical views expressed are supported by quotations not merely from Jâbir but from still earlier alchemists of the Alexandrian school. Abu'l-Qâsim himself seems to have been a good experimentalist and a comparatively logical thinker, but his general views often represent a retrograde movement upon those of Jâbir.

Aidamir al-Jildakî, who also lived for part of his life at Cairo, is of importance chiefly on account of his extensive and deep knowledge of Muslim chemical literature. He apparently spent the major portion of his existence in collecting and explaining all the books upon alchemy which he could discover, and his labours have now begun to receive their reward, for his writings form an indispensable source of a great deal of our knowledge of chemistry and chemists in Islâm. In a few instances it is possible to observe that he must have carried out experimental work himself, but for the most part his books are commentaries upon the works of earlier writers. Thus his great *Nihāyat al-Ṭalab* is a commentary upon Abu'l-Qâsim's *Kitâb al-Muktasab,* and although his explanations are not seldom more obscure than the passages they are intended to throw light upon, he had the admirable habit of making innumerable and lengthy quotations from Jâbir, Khâlid, Ibn Arfa'Ra's, Maslama al-Majrîṭî and many other authors, and his books are thus a rich storehouse of information on Muslim chemistry. It is therefore necessary to enquire into the question whether his quotations and historical facts are authentic, and whether his reliability is to be accepted or doubted. Fortunately, it often happens that a book from which he quotes is extant, and his quotations in such cases can be checked. A test conducted on these lines has shown that Al-Jildakî was conscientious, and although he does not always come through unscathed, his general trustworthiness can be safely assumed. A case in point has been described above, where, it will be remembered, his assertion that Avicenna had written against the transmutationists in his book *Al-S̱hifā'* was shown to be true. Al-Jildakî thus deserves the warmest thanks of all those who are interested in the history of chemistry.

This little sketch of Muslim chemistry has drawn attention to some of the principal lacunae in our knowledge and to a few of the chief problems which await solution. The main need is for more recruits to this very fruitful field for investigation; the mass of material available is far too great to be thoroughly studied in detail by the present handful of workers, and yet the study of Arabic science is the most important task before the modern historian of the growth of civilisation.

H. J. J. Winter

THE ARABIC ACHIEVEMENT IN PHYSICS*

On the decline of the Roman Empire, and particularly after the closing of the schools of learning in Athens in the year A.D. 529 by the Emperor Justinian, the legacy of Greek science passed to the East, mainly owing to the efforts of the Nestorians in such centres as Antioch, Edessa, and Nisibis, and to a lesser extent through the waning Alexandrian School in Egypt. Nestorians were particularly well received at the Sāsānian capital of Jundīs͟hapūr in southwest Persia, and here arose a great centre of learning, where east and west mingled, and where the Greek rationalist outlook on the universe held its own against oriental mysticism until the triumph of Islām. When, on the establishment of the 'Abbāsid caliphate in Bag͟hdād, the leadership in culture passed to that city around A.D. 750, the scientists of Islām were able to build their knowledge upon both the geometrical methods of the Greeks and the analytical approach of the Hindus—though they generally favoured the former, which indeed proved ultimately to be a limitation, as it had been with the Greek themselves.

* Reprinted from *Endeavour,* IX, 34 (1950), pp. 76-79, with the permission of *Endeavour* and of the author. The figure which accompanied the original article has been omitted.

The Arabic language was an admirable medium for the transference of the new thought, and during the period A.D. 750-900 the classics of Greek physics were sought out, translated with commendable industry, and sometimes improved upon. Moreover, algebraical and trigonometrical ideas were derived from the Sanskrit. During this time of translation, some of the physical works of Aristotle were made available by Hunain ibn Ishāq (809-877) and his many collaborators; Al-Kindī wrote an improved version of the *Optics* of Euclid; T͟hābit ibn Qurra studied the "Roman" steelyard; and the Banū Mūsā (the three sons of Musa ibn S͟hākir) completed *c.* 860 *The Book of Artifices,* a treatise on mechanics. Indeed, it will be seen presently that the Arabic contribution to physics was mainly in optics and mechanics, particularly the former.

Arabic science reached its zenith between about A.D. 900 and 1100, and in this phase we encounter a galaxy of great intellects: men of wide learning, tolerance, and travel, who mastered all the knowledge of their day and reproduced it in their encyclopaedic writings. Among them were Ar-Rāzī (Rhazes), a celebrated physician, who also studied optics and the properties of matter and motion, space, and time; Ibn Sīnā (Avicenna), 980-1037, eminent as philosopher, physicist, and physician, who wrote a great work on physics, a beautiful copy of which was obtained by Sir Francis Younghusband from the oasis of Yarkand and is now with the Royal Asiatic Society; Ibn al-Hait͟ham (965-1039), one of the greatest optical students of all time; and Al-Bīrūnī ("The Master") —973-1048—a contemporary of Firdausī at the Court of Mahmūd of Ghazna. Al-Bīrūnī was a many-sided genius, whose work in several branches of learning remains classic, and who made in particular a careful study of the specific gravities of metals and precious stones.

We select Ibn al-Hait͟ham, known in medieval Europe as Alhazen, for particular note. Born at Basra, he spent the last years of his life in the vicinity of Al-Azhār in Cairo. His greatest work is the *Optics* (*Kitāb al-manāzir*), a Latin version of which ap-

peared in 1572.[1] Until lately the Arabic original was believed lost, but a manuscript has been found in Istanbul and is the basis of some recent researches by Mustafā Nazīf Bey.[2] Al-Haitham not only improved upon the knowledge of optical reflection inherited from the Greeks, but was the first to make an elaborate investigation of refraction. By competent mathematical investigation he extended the laws of reflection, which had been considered mainly by Euclid and other Greek thinkers in relation to plane mirrors, to the case of concave and parabolic mirrors,[3] and he undertook the actual construction of steel reflectors by means of a kind of lathe. In this way he was able to discover spherical aberration (though he failed to consider the caustic curve), and, on the basis of the conics of Apollonius, to establish an exact focus in the case of the paraboloid. This happy combination of analysis and synthesis places Al-Haitham among the great scientists. His methods influenced not only some of his successors in the east, but also Robert Grosseteste, John Peckham, Roger Bacon, Witelo, Leonardo da Vinci, and Johannes Kepler in the west. The application of rigid mathematical methods to physical problems enabled Al-Haitham to determine the point of reflection on a concave spherical mirror when the positions of the object and the eye are known; the resulting equation of the fourth degree was solved by the intersection of a circle and a hyperbola. The elaboration of such work, involving cubic equations, from the initial treatises of Archimedes and Apollonius, was a unique Arabic achievement, leading to a solution of certain physical problems and to the greatest algebraical treatise of medieval times, the *Algebra* of 'Umar Khayyām. The first use of the camera obscura is ascribed to Al-Haitham; he also made a study of the onset of twilight,[4] in which he gives 19°

[1] *Opticae Thesaurus Alhazeni Arabis libri septem* (Basel 1572).
[2] Nazīf Bey, M. *Al-Hasan ibn al-Haitham* (2 vols., in Arabic) (Cairo, 1942-3).
[3] Winter, H. J. J., and 'Arafat, W. *J. Asiat. Soc. Beng.*, 15, 1-2, 1949.
[4] *De Crepusculis et Nubium Ascensionibus*, transl. Gerard of Cremona (Lisbon, 1542).

as the angle of depression of the sun below the horizon for its occurrence; and he gave the luminous object as the source of light, as did Ibn-Sīnā and Al-Bīrūnī, in contradistinction from Euclid and Ptolemy, who had believed that the rays originated from the eye.

The new departure made by Al-Haitham lay, however, in the subject of refraction. A remarkable experimental investigation of refraction had been made in antiquity and is generally attributed to Ptolemy, but Al-Haitham's work reads in places like a seventeenth-century treatise. He related the change in direction of a ray of light on entering a medium of different density to an alteration in the velocity of the light, the light travelling more slowly in the denser medium; there were two properties, transparency and density, the former facilitating motion, the latter retarding it. By imagining the velocity of the incident ray to be the resultant of two components, one in the direction of the normal to the surface of separation of the two media and the other parallel to that surface, he was able, by reducing the latter velocity, to account for a position of the refracted ray nearer to the normal when the second medium is the denser, and, conversely, for a movement of the ray away from the normal when the second medium is the rarer. It is interesting to note that while Al-Haitham's interpretation accorded with experimental fact, Sir Isaac Newton's theory, of some seven hundred years later, did not; for Newton, assuming that light consists of corpuscles endowed with great velocity,[5] increased the normal component of this velocity so that the resultant value became greater in the denser medium. Newton's investigations into the nature of light, however, were more profound, for Al-Haitham hardly went beyond the fact of a very great velocity. There are, nevertheless, five outstanding features in Al-Haitham's work: firstly, he was clearly aware of the principle of inertia, later stated as Newton's First Law of Motion, in his conception of the path of a ray of light; secondly, his handling of the mechanism of refraction reveals a competent knowledge of the rectangle of forces,

[5] Ibn Sīnā had also used this hypothesis.

though he does not seem to have considered the possibility of altering the normal component of the velocity as Newton did; thirdly, his statement that a ray of light takes the path, through a medium, which is the "easier and quicker," brings him near to Fermat's principle of least time; fourthly, he knew the first law of refraction, that the incident and refracted rays and the normal to the surface of separation lie in the same plane; and finally, though he failed to discover the second law, which Snell found in 1621, his experimental results indicate that he handled apparatus competently and fully realized the necessity of the empirical approach to knowledge. It is a pity that Al-Haitham did not perceive the sine relationship. The Greek method of reckoning by chords, and the sine of an angle (*jyā*) as used in the Hindu Siddhāntas, had already become known to the Muslim scientists; in particular, Al-Battānī, of Sabian origin, who died in A.D. 929, had already extended trigonometry to spherical triangles. Al-Haitham also investigated the magnification produced by a lens, and the phenomenon of atmospheric refraction.

In the year 1258 Nasīr ad-Dīn at-Tūsī[6] was appointed chief astronomer, and an observatory was erected, at Marāghah in Adharbaijān, on the order of the Mongol, Hulāgū Khan. With the aid of assistants gathered from Damascus, Mausil, Tiflīs, and Kazvīn, At-Tūsī made beautiful astronomical instruments of exquisite workmanship, and completed, under Abaqā Khān, the famous Ilkhānian astronomical tables. At-Tūsī, as one might expect, was also interested in optics, and wrote about reflection, making a version of the *Optics* of Euclid as Al-Kindī had done earlier, but he seems to have failed to understand refraction; he was primarily a geometrician in outlook and was restricted by Euclidean methods. One of his pupils, Qutb ad-Dīn ash-Shīrāzi (1236-1311) did, however, study the refraction of light in the raindrop, and was instrumental in calling the attention of his own pupil, Kamāl ad-Dīn al-Fārisī (died *c.* 1320), to the *Kitāb al-Manazir* of Al-Haitham,

[6] Nasīr ad-Dīn (1201-74) of Tus in Khurāsān. Many of the "Arabic" scientists were actually Persians: we use the term Arabic rather than Arab.

Book VII of which, on refraction, had apparently been ignored. Al-Fārisī, in the early fourteenth century, made an abridgment from an autograph copy of Al-Haitham, and then wrote a valuable commentary with his own observations, entitled *Tanqīh al-Manāzir.*

Questions on optical refraction had engaged the attention of Muslim scholars in the first half of the thirteenth century, owing to the enthusiasm and broad outlook of Frederick II of Sicily, who linked Islām with Latin Christendom. His influence lasted, long after his burial in Palermo in 1250, well into the fourteenth and fifteenth centuries. He was—with Raymond I, Archbishop of Toledo, in the twelfth century, and Alfonso X of León and Castile in the late thirteenth century—one of the agents who inspired the translation of Arabic treatises, some on physics, into Latin. In correspondence with scholars in the Muslim world Frederick II posed questions such as: Why do oars immersed in water appear bent? Why does Canopus appear larger when near the horizon, even when the atmosphere contains no moisture? Frederick's foundation of the university of Naples in 1224, with its collection of Arabic manuscripts, and his transmission of translations to Bologna and Paris, were instrumental in bringing the latest Muslim ideas into Europe; no doubt the optical theories of Witelo and Roger Bacon owe something to the university of Paris.

By 1150 Arabic science was generally in decline. There did come to fruition, however, the line of development initiated in the ninth century A.D. by the Banū Mūsā, namely the Muslim application of Hellenistic mechanics. There was not much originality in theory, but there were ingenious and beautiful contrivances based upon the *Mechanics* of Hero of Alexandria and the *Pneumatics* of Philo of Byzantium. Great attention was paid to the determination of specific gravities, using the principle of Archimedes; to problems arising out of the use of the lever and balance; to clepsydras or water-clocks; to water-wheels; to fountains; and to various other automata. As early as 807, an elaborate water-clock had been presented to Charlemagne by the Caliph Hārūn ar-Rashīd. About the middle of the twelfth century, a clock was installed in the Bāb

Jairūn at Damascus, and this clock became famous; Ibn as-Sā'ātī wrote a book about it in 1203. Just after the beginning of the thirteenth century there were written the two chief Arabic works on mechanics, namely the *Kitāb mīzān al-hikma* of Al-Khāzinī of Merv, and the *Kitāb fī ma'rifat al-hiyal al-handasīya* (*c.* A.D. 1205) of Al-Jazarī. The former dealt with the measurement of time, with the theory of the lever (continuing the work of Thābit ibn Qurra), with capillarity, and with gravity, which was supposed to be directed towards the centre of the universe and to affect the sea and the atmosphere; it gave also tables of specific gravities of liquids and solids. Al-Jazarī was more technological, treating mainly of clepsydras, fountains, and other contrivances operating on hydraulic principles. The glorious achievement of the 'Abbāsid caliphs such as Al-Ma'mūn (813-833) at Baghdād was emulated in the following century by the Umayyad dynasty in Spain, notably by Al-Hakam at Córdoba (961-976). Córdoba was "the Jewel of the World" in the tenth century, the cultural focus of Europe, where one could walk for ten miles in a straight line by the light of the public lamps. Spanish Muslims, in particular Al-Zarqālī (*c.* 1029-87), made fine scientific instruments, including astrolabes. The astrolabe occupies a key position in medieval astronomy, and although a discussion of its merits is outside the scope of this article, it is indicative of the skill attained by the Muslim instrument makers, who were frequently physicists and astronomers as well. This skill was still being exercised in the observatory of Ulūgh Beg at Samarkand in 1437.

Outside optics and mechanics the medieval world achieved little in physics, the other branches of the subject not having been freed from various metaphysical speculations or generally reduced to mathematical expression. Jābir ibn Hayyān commented in the eighth or ninth century on the nature of magnetic force; and though the derivation of the magnetic compass may be Chinese, it was first widely used for navigational purposes by Muslims in medieval times, and is mentioned by Alexander Neckam, who died in 1217. Apart from the outstanding researches of Ibn al-Haitham,

the general temper of physics was Aristotelian, as we find it in many of the Arabic encyclopaedic and philosophical works, such as those of Al-Kindī, Al-Fārābī, Ibn Rushd (Averroës), and Ibn Sīnā, and of the Brethren of Sincerity (Ikhwān as-Safā'), Aristotle's *Meteorologica* led to a "meteorology" of wide generality, embracing what we should now define as meteorology together with perspective, which latter involved both physical and physiological optics. Large-scale natural phenomena, such as the tides, commanded attention, and many successful measurements were made in physical geography. The theory of the rainbow, especially, figures throughout Arabic physics from Al-Kindī to Ash-Shīrāzi, initially in terms of reflection on the basis of Aristotelian and Euclidean ideas, and finally incorporating the theory of refraction which derived from Ibn al-Haitham. Musical intervals were studied by Ibn Sīnā, who wrote about them in his *Kitāb ash-Shifa'*.

H. J. J. Winter

MUSLIM MECHANICS AND MECHANICAL APPLIANCES*

Of the Greek authors whose writings on mechanics were rendered into Syriac and Arabic during the period of translation and assimilation (roughly A.D. 750-900), Euclid, Archimedes, Apollonius, Hero, and Philo were the most revered. The "Mechanics" of Hero of Alexandria (translated about 860 by the Nestorian Christian, Qusta bin Lūqā of Baalbek, for the caliph al-Musta'īn), and the "Pneumatics" of Philo of Byzantium, the translator of which is unknown, inspired both new writings and a wide range of practical devices. Thus the Banū Mūsā, the three sons of Mūsā ibn Shākir (who was himself a friend of the caliph Al-Ma'mūn), were the authors of the "Book of Artifices" (*Kitāb al-ḥiyal*),[1] which describes one hundred pieces of technical equipment. The greater proportion were novelties, following Philo, and can be classed as mechanical toys, but some of the inventions developed from the ideas of Hero had great practical significance. In medieval Islām during the ensuing period (*c.* 900-1100)—when science was widely accepted and new advances were being made—applications were made of all

* Reprinted from *Endeavour,* XV, 57 (1956), pp. 25-28, with the permission of *Endeavour* and of the author. Figures which accompanied the original article have been omitted.

1 Hauser, F. Das Kitāb al-ḥiyal. *Abh. Gesch. Naturw. Med.,* 1922.

the simple machines such as the lever, wheel and axle, pully, inclined plane, toothed wheel, endless screw, siphon, and pump, together with the water-wheel and windmill.

The so-called Golden Age of Islamic science owed its importance largely to the Persian contribution. The language of Iran had assumed a new significance, and a creative spirit was being born in her scholars as the tenth century dawned. Among those who wrote eloquently in this language rich in imagery were Ibn Sīnā (980-1037), Abū Raiḥān Al-Bīrūnī (973-1048), and 'Umar Khayyām (d. *c.* 1123), though their scientific works are largely in Arabic, a medium better suited to terse and deductive argument. To the Arabic language we also owe a great debt for its preservation of the classics of Greek science.

In the realm of mechanics Ibn Sīnā is noted mainly for his theoretical postulates, our subject representing to him the lowest level of a great scheme of speculative philosophy. These postulates are highly ingenious and sometimes correct. He wrote in *Al-kitāb al-najāt* that "no body begins to move or comes to rest of itself," a clear statement of the principle of inertia; that "time cannot be imagined without movement"; and that force is measurable only in terms of its effects. Again, in any simple machine, "what is gained in power is lost in speed." Ibn Sīnā also regarded the problems of statics as fundamentally those of dynamics, whence he proceeded to explain the impact of bodies from the standpoint of dynamic forces acting from within the bodies. But in one respect his theory of mechanics proved inadequate, for he thought only in terms of uniform velocity, as did Aristotle and Al-Kindī before him. By regarding time as continuous, and as being interpreted in terms of the "quantity of circular motion" of the celestial sphere, he was diverted by these basic assumptions from any consideration of either acceleration or centrifugal force. The significance of Newtonian mechanics, and the reason why it enabled the foundations of modern science to be established, rest precisely in these two latter phenomena, whereby the false postulate that a prime

mover or force is required to maintain a body at a uniform velocity in the line of action of the force was overthrown. Despite such weakness in his postulates, Ibn Sīnā was able to work successfully in the immediate practical field, and is credited with a device similar to the vernier.

Al-Bīrūnī, a man of deep erudition and an experienced traveller, is noted especially for his accurate determination of the specific gravities of eighteen precious stones and minerals. These results he studied and tabulated systematically, and it is significant to note that no such tables appeared in Western Europe until the seventeenth and eighteenth centuries, when Boyle's value for the specific gravity of mercury, for instance, was less accurate than that known to the Arabs. Al Bīrūnī used a "conical instrument"—a flask-like vessel with a spout projecting from the neck—to determine the volumes of metals by displacement.

'Umar Khayyām, best known as a poet, but perhaps more deserving of recognition as the author of the finest algebraical treatise of the Middle Ages, has his place in the history of the balance, following Archimedes, Menelaus, and Muḥammad ibn Zakarīyā of Ray, and preceding Al-Muzaffar ibn Isma'īl al-Isfazārī and Abū'l-Fath 'Abd al-Raḥmān al-Manṣūr al-Khāzinī. Since the technique of the balance became a special science in medieval Islām, as, for example, did the study of the rainbow, we shall refer to it when describing the achievements of Al-Khāzinī.

An interesting essay on the vacuum was written by the philosopher Abū Naṣr al-Fārābī.[2] Until recently believed to have been lost, a manuscript of this essay was discovered in Ankara University and is now in the Ismail Sāip Collection (Series I, No. 183 (ii)). Although it refutes the existence of a vacuum it does so only with reference to two particular experiments with flasks containing air and water, and for which experiments the refutation is, in fact, valid. What is most striking in this essay, however, is an analysis of the experimental results based upon the elasticity of

[2] Lugal, N. and Sayili, A. Farabi's article on vacuum. Ankara, 1951.

the air. Indeed, one of the joys of the historian of science who is able to interpret medieval Oriental manuscripts is that of finding among many pages of tedious matter some angle of approach, or perhaps a discovery, unknown to the Latin West. On the other hand, one learns to receive the views of earlier writers on the history of science with caution. Thus Humboldt attributed to Ibn Yūnus the application of the pendulum to the measurement of time, a statement which the writer has failed so far to substantiate from original manuscripts and which is probably untrue. Though the Arabs had splendid water-clocks, and study of the history of their science is always liable to reveal surprising achievements, as in Al-Khāzinī, a precursor of Galileo seems unlikely.

Of the later Islamic treatises on mechanics two are outstanding, namely *Al-Kitāb fī ma'arifat al-ḥiyal al-handasīya* (The book of the knowledge of ingenious geometrical (mechanical) contrivances)[3] by Abū'l-'Izz Isma'īl ibn ur-Razzaz al-Jazarī Bādī'az-Zamān, and *Al-Kitāb mīzān al-ḥikma* (The book of the balance of wisdom)[4] by Al-Khāzinī of Merv. The former is by far the less original but serves as a summary of the various forms of contemporary apparatus; its author was primarily a craftsman, and had advanced somewhat in technique beyond Hero and Philo, being able to use with advantage the work of his Muslim predecessors. Completed in 1206 for the Urtuqid Sulṭan Maḥmūd, ruler in Amida—Al-Jazarī had been in the service of the dynasty since 1181-82—the book was held in esteem by three Urtuqid Sulṭāns and later translated into Persian and Turkish. Main interest centres upon elaborate water clocks for telling the hours and hydraulic apparatus used in the raising of water. A knowledge is shown of the action of paddles, cogwheels, and revolving shafts. In a typical water clock a copper beaker is initially full, the float being at the surface of the water and the weight at the bottom; as the beaker empties the float sinks and the weight rises, thus rotating a central

[3] Coomaraswamy, A. C. The treatise of Al-Jazarī on Automata, Boston. 1924.
[4] Khanikoff, N. *J. Amer. Orient. Soc.*, 6, 1, 1860.

spindle. The rod held by the figure of a scribe passes over an engraved lid, thereby tracing the passage of the hours.

In the year 1860 there appeared in the Journal of the American Oriental Society translations of two remarkable works—the version of the *Sūrya-Siddhānta* of the Hindus, made by Ebenezer Burgess, and the treatise of Al-Khāzinī, just mentioned, first rendered accessible to Western scholars by N. Khanikoff, Russian Consul-General in Tabrīz. This most important occasion has probably been forgotten by most historians of science, and it is refreshing to recall it through the second of these translations. "The Book of the Balance of Wisdom" is one of the great treatises on mechanics. Though it deals principally, and in great detail, with the practice of accurate weighing and the determinations of specific gravities, it also discusses gravitation, flotation, and geodesy. Written at the request of Abū-l-Ḥārith Sanjar ibn Mālikshāh ibn Alpārslān in 1121-22 "for his high treasury," it paid particular attention to the specific gravity of alloy coinage, including *ad hoc* calibration of the balance arm, and it referred to the Archimedean solution of the problem of Hiero's crown. The comprehensive nature of Muslim study of the balance may be seen from this quotation from "The Book of the Balance of Wisdom": "Novelties and elegant contrivances in the way of balances, such as: the balance for weighing dirhams and dīnārs without resort to counterpoises; the balance for levelling the earth to the plane of the horizon; the balance known as 'the even balance,' which weighs from a grain to a thousand dirhams or dīnārs, by means of three pomegranate-counterpoises; and the hour-balance, which makes known the passing [secular] hours, whether of the night or the day, and their fractions in minutes and seconds, and the exact correspondence therewith of the ascendant star, in degrees and fractions of a degree." Hour-balances consisted essentially of a long lever, one arm of which carried a vessel of water emptying in twenty-four hours, the other arm a sliding weight acting as a counterpoise and moving over the calibrations on the arm. It was usual to calibrate the right-hand arm by silver enchased at appropriate distances along it, and the divisions were in units

corresponding to the particular function of the balance, e.g. units of time, values of specific gravity. The Arabs were thoroughly familiar with the application in surveying and building of the parallelism of a balance beam with the plane of the horizon when the beam is evenly loaded.

A further reference to Al-Khāzinī will serve to indicate the extreme care with which specific gravity determinations were carried out. He says: "We have made all our comparisons in one single corner of the earth, namely, in Jurjānīyah, [a city] of Khuwārazm, situated where the river of Balkh becomes low, at its outlet upon the little sea of Khuwārazm, the water of which river is well known, of no doubtful quality, and [all our operations have been performed] early in the autumnal season of the year." [5] Not only was Al-Khāzinī aware of the necessity of removing, as far as possible, the influences of impurity and temperature variation, but he classed the balance with the astrolabe as a precision instrument demanding the greatest care in construction and maintenance, for a good balance detected 1 mithqāl in a total of 1000 mithqāl; and he suggested about 4 bazaar-cubits (2 metres) as the length of the beam, "because length influences the sensibility of the instrument," and 1 cubit as the length of the pointer. Use of a scale and pointer was probably first suggested by Muḥammad ibn Zakarīya of Ray. By the time of Al-Khāzinī five thin hemispherical scale-pans, made of bronze, were in use with the balance, two being permanent, two additional, and one movable along the right-hand arm, their function being to cover all the various determinations involving weighing in liquids, etc. Commercial applications largely concerned the specific gravities of alloys and gems. Some of Al-Khāzinī's results are shown, in modern terms, in the accompanying table, and without attempting any critical analysis of their accuracy we see at once that they are remarkably close to values now accepted:

[5] Khanikoff identified this place with the site of Kuna-Urghenj. It appears that by the twelfth century A.D. the Oxus emptied into the Sea of Aral and not into the Caspian.

Gold	19.05 (cast)	Fine pearl	2.60
		Ivory	1.64
Mercury	13.56	Sweet water	1
Brass	8.57	Water (boiling)	0.958
Emerald	2.75	Olive oil	0.920

The areometer of Pappus in an accurate form was also well known to Al-Khāzinī. Consisting of a uniform hollow copper tube, weighted at one end with a hollow cone of tin, and with two ends "resembling two light drum skins," it floated vertically in liquids, being calibrated in both values of specific gravity and of volumes displaced. An interesting diversion made by Al-Khāzinī was to calculate the weight of the Earth were it to consist solely of gold, for "truly there will not be accepted as ransom from those who were infidels and died infidels as much gold as would fill the earth; for them are severe pains; they shall have no defender" [Qur'ān, III, 85].

Finally, we may examine Al-Khāzinī's views on gravitation. Although he followed in the tradition of Archimedes, Euclid, Menelaus, Ibn Al-Haitham, and Abū Sahl al-Kūhī, his views were unusually advanced for a medieval scientist, and in spite of the errors which they undoubtedly contain, the insight of their author cannot fail to compel respect. Thus, "heaviness is the force with which a heavy body is moved towards the centre of the world" and "a heavy body is one which is moved by an inherent force, constantly, towards the centre of the world" [Lecture I, Chap. I, Sect. I]. Further, "That point in any heavy body which coincides with the centre of the world, when the body is at rest at that centre, is called the centre of gravity of that body" [Lecture I, Chap. I, Sect. 4]. The Aristotelian hypothesis on motion, however, died hard: "Bodies alike in gravity are those which, when they move in a liquid from some single point, move alike—I mean, pass over equal spaces in equal times" [Lecture I, Chap. I, Sect. 4]. Again, "the weight of any heavy body, of known weight at a particular

distance from the centre of the world, varies according to the variation of its distance therefrom; so that, as often as it is removed from the centre, it becomes heavier, and when brought nearer to it, is lighter . . ." [Lecture I, Chap. V, Sect. 3]. Such statements as the last two remind us that we are not yet in the realm of modern science, for in the latter case Al-Khāzinī had in mind the fact that as the atmosphere became rarer, the upthrust exerted by displaced air would be reduced. In fact he assumed that air has weight, although he attempted no measurements.

The Arabs widely exploited natural sources of power, windmills and watermills being constructed where climate and geography permitted.[6] Thus, according to Mustaufī, "10 leagues to the north of this city (Nishapur) is a mountain from which flows a river which causes several mills to turn with great speed," while Marrākeshī states that "there are in the city (of Marrakesh) and even under the surrounding walls, some three hundred water-mills." In Afghanistan, where the winds blew without cessation, carrying great clouds of sand, nature's tremendous forces were recognized and harnessed. Al-Mas'ūdī (*c.* 947)[7] referred to the value of the windmill, as did Al-Istakhrī a little later; and a full description was given by Al-Dimashqī in the thirteenth century: "The inhabitants use the wind for turning the mills and for the removal of sand from one place to another. They erect a high building like a minaret; or they use a high summit of a mountain or a similar prominence or a tower of a castle, and upon this raise up a building. In the building is a mill which revolves and grinds, while below is a toothed wheel which is caused to rotate by the useful action of the wind. The wheel rotates below, thereby driving the mill above." Windmills were also used to raise water from wells in order to irrigate the gardens. Whereas water-mills are mentioned in Vitruvius, Book X, Chap. 10, and were perhaps invented in the time of

[6] Wiedemann, E. Zur Mechanik u. Technik bei den Arabern. *S.B. phys.-med. Soz. Erlangen,* 38, 1, 1906

Idem. Zur Technik bei den Arabern. *Ibid.,* 38, 307, 1906.

[7] de Meynard, C. Barbier, and de Courteille, Pavet. Les Prairies d'Or, II, 80. (Société Asiatique, 9 vols.), Paris, 1861-77.

Augustus, it seems likely that the windmill was an Islamic application of later date. The latter was certainly referred to by Al-Masʿūdī as though its use were commonly accepted in Afghanistan. It is possible that the windmill was known in Arabia as early as the first half of the seventh century A.D.

Henry E. Sigerist

MEDIEVAL MEDICINE*

We can approach the medical history of a period from different points of view, from that of practical achievements or from that of ideas. Medicine is a craft and a science. As a craft it is frequently transmitted by word of mouth and practical instruction, from father to son and from master to pupil. As a science medicine is one aspect of the general culture of a period. It reflects man's attitude toward nature, toward the phenomena of life and death. It is expressed in literary form, and the medical books represent one aspect of the literature of a period sharing its general style. We may be more interested in the health conditions and health hazards of a period and in the treatments and diets applied to cure disease or to prevent it. Or, we may be more attracted by the ideas that guided the physicians' actions. In the following brief sketch of medieval medicine I shall not be able to discuss its practical attainments in a more than cursory way. Rather, I will try to determine the place of medieval medicine in the history of civilization.

Our symposium has a serious gap in that it jumps from ancient

* Reprinted from *University of Pennsylvania Bicentennial Conference: Studies in the History of Science* (Philadelphia, 1941), pp. 43-54, with the permission of University of Pennsylvania Press.

Egyptian to medieval medicine and has omitted a discussion of Greek medicine. And yet it was Greek experience and Greek thought that constituted the basic content of medieval medicine. Greek medicine was transmitted to the medieval world and was gradually assimilated by it. A synthesis of rare harmony was achieved between Greek and medieval views until, in the Renaissance, the Western world revolted against traditions. Let us examine this process.

TRANSMISSION

We must remember that medieval medicine had two centers of development, the Muslim empire in the East and the Christian world in the West.[1]

In the seventh century A.D., Arab tribes, driven from their homeland by the aridity of the soil, united and disciplined by a new creed, moved north seeking more fertile lands. They conquered Cyria, turned west, conquered Egypt, the whole coast of North Africa, went over to Spain, crossed the Pyrenees, until they were stopped in France. In less than a century they had founded an empire that reached from the Pyrenees to the Indus River. They were tolerant. No one was forced to embrace the new religion, but the infidel was a subject, heavily taxed. It was highly profitable to become a Mohammedan. The convert acquired Arabic citizenship and became a member of the ruling class. Millions adopted a religion which, after all, was not so different from Christianity. The new empire was united by a common faith, disciplined by religious rites and, since the Koran was not to be translated, it had a common language.

The Arabic conquerors were a rough crowd, horsemen, warriors, poets at times, but little experienced in the arts and crafts. They

[1] If I speak of East and West, I do it for the sake of brevity. I am well aware that throughout the Middle Ages there were Mohammedans in Spain and Christians in Syria.

soon found that the people they had subjugated had better architects, painters, engineers, and physicians. They hired them and soon began learning from them. Alexandria, although the famous library had been destroyed before the conquest, was still a center of learning. It was obscured by mystic currents but was backed by a great tradition; Paulus of Aegina, the last great Greek medical compilator, lived there in the first half of the seventh century.

More important because it was infinitely more dynamic was another intellectual center, Gondeshapur, in Persia. A foundation of Sassanian kings, it had become an asylum for refugee scholars. Greek philosophers driven from Athens by Justinian, Christian heretics, Nestorians, driven from Nisibis, convened in Gondeshapur where they came in touch with Persian and Indian thought. Of all the sciences medicine was probably the most flourishing, centered around a hospital and an academy. Syriac had become the language of learning in Western Asia, and many classics of Greek philosophy, science, and medicine were translated into Syriac.

And so the Arabs found in the territory of their conquest not only intellectual centers, but they found in addition the chief Greek medical literature already translated into a Semitic language. Books were the source of knowledge, and the delivery of books, particularly of alchemical and medical books, was more than once made a condition of peace treaties with the Byzantine empire. Once a book was available in Syriac version it was an easy matter to have it translated into Arabic. After this was done, the book could be read and used by all who needed it from the Pyrenees to India.

In the second half of the eighth and throughout the ninth century an endless number of Greek books were translated in this way: the works of Galen and his successors, but also Hippocratic writings and the Materia Medica of Dioscorides, the latter gorgeously illustrated and a book that is still consulted in the Orient today. The chief "transmitter" was Hunayn ibn Ishaq, who was head of a regular school of translators in Baghdad, at the court of the Abbasid caliphs. He was assisted by his son Ishaq and his nephew Hubaysh, and tradition attributes to him over ninety pupils. Most

of these translators were Christian scholars. They were the linguists of the day, mastering Greek, Syriac, Arabic, and often Persian. They usually first translated a book into Syriac for the use of their fellow Christians, then into Arabic for the use of Muslims. Just as the Ptolemies in the third century B.C. had sent out regular expeditions in search of Greek manuscripts for the Alexandrian library, so did the Abbasid caliphs for the library in Baghdad.

At the end of the ninth century the Arabic-speaking world was in full possession of the Greek medical tradition. It was a medical science that had lost its momentum and had completed its course. It was, moreover, the science of another people, different in race and outlook. Nevertheless, it was the accumulated experience of centuries of observation and reasoning, innumerable facts about diseases and their treatment, that became available to the Islamic world in this way.

Developments were similar and yet different in the West. There too it was hunger that drove barbaric tribes into the fertile fields of the Roman empire and started a migration of nations. The Germanic people that settled in the Western part of the Roman empire had just as primitive medical knowledge as the Bedouins of Arabia. They too all of a sudden came in touch with a much higher civilization. In the East the Arabs went on their conquest with a new religion that was gradually adopted by the subjugated nations. With their religion they took over the conqueror's language, at least as a literary language. In the West the process was different. The Goths were converted to Christianity, which was the official religion of the Roman empire. Its language was Latin, and Latin became for centuries the literary language of all nations that recognized the authority of the Church of Rome.

For over one thousand years medical books had been written in Greek throughout the Graeco-Roman world, and very few Latin medical books were available. But Latin was becoming an increasingly important language. It was the language of the court, the administration, and the church. It was the vernacular language of Italy, Gaul, and Spain, and was the literary language not only in

Germany but in North Africa and Britain. There was a strong demand for medical books written in Latin. Translations were made in the West as in the East, and from the fourth century on a new medical literature developed which was written directly in Latin. It was not original in character, but consisted of compilations, its value depending on the sources used. The West had intellectual centers also. One such center was North Africa, in the fourth and fifth centuries, where Saint Augustine lived and where one of his friends, the physician Vindician, and his pupil Theodorus Priscianus compiled some important books. An African, Caelius Aurelianus, translated Soranus and thus preserved the experience of the Methodist school, the doctrine of which was very influential in the early Middle Ages.

Another such center was Bordeaux, famous for its school of rhetoric. But there were physicians there too, such as Marcellus Burdigalensis, who compiled a very popular collection of prescriptions. Ravenna, the residence of Theodoric, had in the sixth century a medical school, the outlines of which we just begin to perceive. It had Iatrosophistae, professors of medicine, who interpreted the Galenic canon in Latin in the same way as was done in Alexandria in Greek. Oribasius was translated twice in Ravenna, and there can be no doubt as to the importance of this school. Roman institutions did not perish in the early Middle Ages. Many schools flourished in Italy in the Lombard period and became starting points of universities, as was the case in Bologna.

At the time when Harun al-Rashid attracted scholars and artists to his court, Charlemagne did the same in the West and laid the foundation for schools that were to become famous, in Tours, Chartres, Rheims. At the same time Benedictine abbeys, like Monte Cassino, Bobbio, St. Gall, Fulda, were centers of learning where ancient literature was studied, copied, and passed on from generation to generation.

There can be no doubt, however, that the Muslim world was far ahead of the Western world in the early Middle Ages. Around 900

the Arabs were in full possession of the Greek medical tradition. In the West some works of Hippocrates and Galen, the Materia Medica of Dioscorides, Soranus and some other great writers were translated as early as the sixth century, but around 900 they were almost forgotten. The popular literature consisted of short treatises compiled for practical purposes in Greek in the fourth century mostly, translated into Latin in the sixth century. They were translated into Syriac, Arabic, and Hebrew also, but were superseded by better literature. In the West, however, these short treatises dealing with urine, pulse, fever, diets, prognostic, bloodletting, and pharmacology constituted the bulk of ancient literature that was still alive in Carolingian days.

Dioscorides, the chief source of ancient materia medica, was translated three times in the early Middle Ages, but of one verison we have only an indirect testimony. A second version is preserved only in short fragments, and of the third only two manuscripts have survived, while we still have over fifty manuscripts of the herbal of Pseudo-Apuleius. This shows how infinitely more popular this very inferior treatise was. The prognostic of Hippocrates was translated twice, but both versions are known only in short fragments while there are many manuscripts of the so-called *Prognostica Democriti.*

In 732 the Arabs were expelled from France, but they remained in Spain until 1492. They conquered Sicily in 827 and ruled the island until the end of the eleventh century. From the eleventh to the thirteenth century East and West clashed in the crusades. Intercourse between the two civilizations became very close. Different as they were, they had a great deal in common due to their common heritage. Not only commercial but also intellectual relations increased and, since the Arabs were more advanced in science and medicine, Europe began to learn from them.

In the eleventh century, Constantine, an African by birth and therefore a master in Eastern languages, traveled all over the Orient and came to Monte Cassino where he became a monk, bringing

with him Arabic medical books that he translated into Latin. He thus greatly enriched Western literature and made Greek and Arabic writers available that had not been known before.

Toledo, one of the chief centers and the Western outpost of Arabic learning, was conquered by Alfonso VI of Castile in 1085, but it maintained its position under Christian rule. It thus became the center from which Eastern knowledge was transmitted to the West. In Toledo in the twelfth century Gerard of Cremona and his students translated a large number of Greek and Arabic medical, scientific, and philosophic writers from Arabic into Latin. In the early thirteenth century the Western world possessed the Greek medical tradition as the Arabs had done three hundred years before, and possessed in addition the experience of many Arabic scholars.

ASSIMILATION

The Greek medicine that was transmitted to the Middle Ages, in the East and in the West, was the result of a development of over one thousand years. All schools of thought from the early pre-Socratic philosophers to Plato, Aristotle, the Stoics, Epicureans, and Skeptics, to the vagaries of Neo-Platonists and Neo-Pythagoreans, were reflected in some way or other in the physicians' theories. This enormous mass of literature was transmitted in a relatively short period of time, in a haphazard way without any order. A book was translated when good manuscripts were available. This determined the choice first of all. Hunayn ibn Ishaq translated one day the Hippocratic Aphorisms, a book written around 400 B.C., and some other day he made a version of a Galenic treatise written almost six hundred years later. Gerard of Cremona within a few years rendered such disparate books in Latin as the *Techne iatrike* of Galen and the *Liber Almansorius of Rhazes*. This new literature was taken over, not as a collection of historical documents, but as a living whole. It was studied not by

medical historians, but by physicians desirous of learning from it how to treat their patients and how to comprehend the phenomena of health and disease. Viewed from such an angle, the Greek medical tradition was extremely bewildering. It was full of contradictions. Many descriptions of diseases and many prescriptions were unintelligible. A theory that a Greek physician familiar with the philosophy of Pythagoras found easy to understand seemed strange and foreign to an Arab or Christian cleric of the early days. A great deal of interpretation was required before this new learning could be assimilated.

Dictionaries were written for the elucidation of difficult terms or concepts, commentaries to explain authoritative texts, concordances in which similar opinions were brought together, conciliatores to reconcile divergent views. Such books were written in the East and in the West.

The Greek tradition, however, carried to the Middle Ages not only doctrines but basic observations and methods. It taught that disease is a natural process not essentially different from physiological processes. It taught further that the human body has a natural healing power which tends to overcome lesions and to restore the lost balance of health, that all actions of the physician must therefore be directed toward aiding this *vis medicatrix naturae*. The Greek tradition taken as a whole, regardless of doctrines, taught how to approach a sick man, what questions he should be asked, how to examine him, and how his symptoms must be evaluated so as to know what fate has in store for him. Greek medical literature of all periods was full of unsurpassed descriptions of disease symptoms and disease pictures. And it contained a wealth of information concerning the treatment of diseases—dietetic, pharmacological, physical, and surgical—the result of centuries of experience. Once this knowledge was assimilated medicine could advance. And it did, in the East and in the West.

The tenth and eleventh centuries were the Golden Age of Arabic medicine. The leading physicians were no longer Christians but Muslims. They came from all parts of the empire, many of

them from Persia. Hospitals were built in increasing numbers from the ninth century on. They were not poorhouses or almshouses like the Western hospitals of that period. They were places where sick people were treated, where physicians gathered experience and instructed students.

The number of Arabic-writing physicians who enriched medical knowledge is large. Many of their writings are lost or still buried in manuscripts. Let me mention only a few names and a few contributions. Al-Razi (Rhazes), probably the greatest Muslim clinician, was an extremely versatile scholar, physician, scientist, philosopher, and theologian. We admire him not so much for his *Continens,* an encyclopedic textbook of medicine, as for his case histories, monographs, and short treatises in which he established new disease entities. Most famous is his book *On Smallpox and Measles,* remarkable also his treatise *On Stone in Bladder and Kidneys.* Many more are still unpublished. Rhazes' medical doctrine was Greek, to be sure, but by applying Greek methods of clinical observation and research he enriched medicine considerably.

Another distinguished clinician of the period was Ali ibn el-Abbas (Haly Abbas), like Rhazes a Persian. He too wrote a comprehensive textbook of medicine which is full of valuable observations and reflections. He took a critical attitude toward his predecessors, Greek and Arabic, and accepted from them what he considered true.

All sections of the empire contributed to the Golden Age of Arabic medicine. An Egyptian Jew, Isaac, wrote important monographs on fever, urine, diets, and drugs. One of his students, Ibn al-Jazzar, became well known for a little book in which he gave dietetic advice to travelers. It was translated not only into Latin but also into Greek and Hebrew. The greatest surgeon of the period, Abu'l Kasim, was born in Spain, in El-Zahra near Cordova. He was influenced by Greek writers, notably Paulus of Aegina, but was an experienced surgeon himself. Materia medica was greatly enriched by Arabic writers. An empire that covered such a vast

territory yielded drugs from all climates. A mere list of Muslim physicians who contributed to the subject would fill many pages and include names from all provinces.

The Greek tradition was assimilated in the West also, but later than in the East and in a somewhat different way. As we mentioned before, it was transmitted, not in its pure form, but after having gone through the Arabic channel. The experience of the Greeks was made available to the Western Middle Ages together with that of the Arabs. Constantinus Africanus in the eleventh century translated not only works of Hippocrates and Galen but also those of Rhazes, Isaac Judaeus, Ibn al-Jazzar, and other Arabic writers.

Constantinus' work marks a turning point in Western medieval medicine. It became known in Southern Italy just at the time when the School of Salerno was developing vigorously. Salerno was a trading town where Greek was heard in the streets and where Western and Eastern influences converged. A group of physicians, laymen and clerics, were practicing in the town, sought by patients and by students from all over Europe. In response to a strong demand for a richer medical literature they compiled books such as the *Passionarius Galeni* which, however, still had all the characteristics of the early medieval literature. The translations of Constantine acted as a strong stimulus. They found in Salerno a group of physicians that was ready to absorb and assimilate them. The literature that Salerno produced in the twelfth century started a new movement in Western medicine. The many books they wrote on all subjects of practical and theoretical medicine reveal that the Salernitan masters had not only assimilated the Graeco-Arabic tradition but had already been able to add observations of their own. It is highly significant that they were fully aware of the importance of anatomical studies. Human bodies were not yet dissected, but those of animals were.

Another important contribution to medicine, though of a different order, came from Southern Italy. Frederick II in his *Constitutiones* of 1240 set definite standards for the practice of medicine by requiring a prescribed curriculum of nine years, examination by

the Salernitan masters in the presence of a representative of the state, and by licensing the medical profession. This gave it a status it had not had before.

When Gerard of Cremona and his group were at work in Toledo, another medical school had come into existence not far from Spain, in Montpellier. Just as Salerno had profited by the first wave of translations, Montpellier did by the second. The interpretation and assimilation of this new literature became one of the chief tasks of the young Western universities.

If we wish to watch the medieval physician at work, we must not only consult the textbooks. Textbooks, even in our days, always have to a certain extent the character of compilations, since no man's original researches can cover an entire field. We must read the *Consilia,* missives in which a doctor discussed a definite case. Or we must watch him fighting epidemics. When the Black Death ravaged Europe in 1348, the physicians had to face a problem for which ancient medicine did not give any solution. Or we must look at the surgeon operating on a soldier after a battle.

When we do this, we soon find that Western medicine too had absorbed the Greek tradition and was enriching it by many important observations.

SYNTHESIS

So far we have spoken of the transmission of Greek medicine and its assimilation and enrichment by medieval physicians. Was this all? Was medieval medicine nothing else but a reminiscence of ancient Greece, a belated outgrowth of Hellenistic medicine? Is it possible for a civilization that is alive to take over ideas and systems which are deeply rooted in another civilization without modifying them? The Middle Ages, in the East and West, produced new forms of expression in the social and economic life, in government, law, theology, art, and literature. Is it conceivable that they could have

left medicine without their imprint? In other words, is there such a thing as an essentially medieval medicine?

Of course there is. A synthesis was accomplished in this field also. So far, little research has been done on the subject and all I can do is to show where this synthesis is to be found.

A work like the *Canon* of Avicenna could not have been written in antiquity. Avicenna, one of the greatest physicians and philosophers of Islam, attempted to build a complete, logical, and well-rounded system of medicine. Its elements are to a large extent Greek—Greek medical experience and thought, Aristotelian philosophy, with a tinge of Neo-Platonism. To this was added the experience of several centuries of Arabic medicine and a great deal of personal experience. With these elements in hand, Avicenna created a system that was no longer Greek but was an expression of Muslim philosophy. It was so forceful and persuasive that it dominated medicine in the East and the West for six hundred years.

In another sphere of medieval culture we find a physician-philosopher, Maimonides, who wrote *Aphorisms according to Galen.* The book is by no means a mere repetition of Galenic doctrines. Maimonides selected passages from Galen. He selected what appealed to him particularly, and the choice he made already reflected his personality. He took a statement from Galen as motif and developed it in his own way, thus creating a synthesis of Greek, Arabic, and Jewish thought.

The same synthetic process can be traced in the works of the Western scholastic physicians of the thirteenth and fourteenth centuries, Albertus Magnus, Roger Bacon, Arnald of Villanova, Pietro d'Abano, to mention only a few. Aristotle, Galen, and Avicenna were their masters. They quoted them constantly and followed their methods. But they did more. They were Christian scholars. Theology was the mother of science and learning, and they succeeded in creating systems in which the experience of medicine became part of the Catholic concept of the world. Their works are essentially medieval.

REVOLT

The parallelism in the development of medicine in the East and in the West is striking but is easily explained by the common heritage and by the whole situation in which both groups of people found themselves in the early Middle Ages. It is much more difficult to explain why this parallelism came to an end.

The Golden Age of Arabic medicine was short. After 1100 there was a steady decline. Factual contributions to medicine were still made and many books were written, but there was hardly any development. People looked backward and not into the future, commented upon their classics and followed traditional patterns of thought. The Islamic world remained medieval to our day, except in the few sections that have recently adopted features of Western civilization.

Matters were different in the West, and the Renaissance marked the turning point. It is a matter of speculation to determine what forces created that great and deep movement. I shall not attempt to discuss the problem in this brief paper. There was a primitive accumulation of capital in the East just as much as in the West, perhaps even more, but it was Europe that developed a capitalist economy. Great voyages of discovery were undertaken by the Arabs long before Europe was thinking of a sea route to India, but the European voyages had a much more profound influence. They affected Western economy deeply and became a stirring experience.

One of the essential traits of the Renaissance was its attitude of revolt against the traditional authorities. The most powerful medieval authority, the church, was attacked and "reformed." The power of the craftsmen's guilds was broken by the developing industry. The authority of the medical faculties was opposed, and their power to regulate the practice of medicine was gradually taken over by other agencies.

Throughout the Middle Ages the Greek medical tradition was

accepted as authoritative. It was open to interpretation, to be sure, but its authority was hardly ever questioned. Now physicians wrote books *De Plinii et aliorum medicorum erroribus*. This revolt against tradition was sometimes dramatic as in the case of Paracelsus. It was usually less spectacular but was a revolt nevertheless, and it paved the way to a new medical science.

Reuben Levy

AVICENNA—HIS LIFE AND TIMES*

Will you allow me to preface what I have to say this evening by acknowledging the honour you do me by your invitation to address your Society, and then by warning you that there is very little which is medical about me except what I have acquired by marriage? What I have to say lays no claim to original research, though a knowledge of Arabic has been of help. For scientific literature that language was the lingua franca of the learned world from India to Morocco and Spain once Islam had established itself there, and scholars whose mother-tongue might have been Arabic, Persian, Turkish, Spanish or any other used it when writing their books. It was the language into which translations were made—through the intermediary of Syriac or Hebrew—when the Caliphs wished to delve into the mysteries of Greek philosophy and medicine. Hence, we speak of Arabian science or Arabian medicine, although it was rarely that a native of Arabia concerned himself with such subjects.

To turn now to Avicenna, which is a mutilated version of the name Abu 'Alī ibn Sīnā. Two years or so ago, the Iranian Govern-

* Paper read before the Cambridge University History of Medicine Society on 27 November 1956. Reprinted from *Medical History*, I, 3 (1957), pp. 249-61, with the permission of *Medical History* and of the author.

ment celebrated the thousandth anniversary of the birth of this great figure of the Islamic world, where he is known as "Al-Shaikh, al-Ra'is" (the Shaikh, the Chief), or as "Al-Mu'allim al-Thāni" (the Second Doctor—Aristotle having been the First). According to Western reckoning the celebration was premature, the birth having occurred in A.D. 980. But the Muhammadan year consists of twelve lunar months, which amount only to 354 days, whereas the year of our era is the solar one of 365 days, with 366 in leap years. However, the authorities explained, since Avicenna was a Muslim it was fitting that his millennium should be reckoned according to the Muslim era, and, whatever the reckoning, the time had come for a celebration. The Arabs and Turks had had theirs, for Avicenna was claimed by Arabs as having been a figure in Arabian science, and by the Turks as having been born in Central Asia. *Now* the Persians wished to do honour to one who had originated in Persian territory and was buried in Persian soil.

We happen to know more about Avicenna than about most of the pioneers of medicine, because he dictated a record of the first twenty-one years of his life to his friend and pupil Juzjāni. This autobiographical material ceased at the time of his father's death, which seems to have brought about a sudden release from his older ways and habits and to have set him off on a more adventurous career. The whole story is to be found in various dictionaries of biography in Arabic and Persian, from which this present account is taken. From it we learn that Avicenna was born in A.D. 980, though some put the year as 985, near Bukhara, the capital of Transoxiana, in a village where his father held a government appointment of some importance, probably as tax gatherer. The capital city itself had long been well endowed with schools, mosques and places of higher learning, and after a time the father moved there, possibly to give his family a good education. By the age of ten, Avicenna had the Koran by heart, and knew so much about Arabic and Persian literature that, as he says himself, "it was accounted a marvel."

While Avicenna was still a child the father had come under the

influence of missionaries of the Isma'ili sect, who at times made use of hashish as an instrument in the propagation of their doctrines and had hence become known to the Arabs as *Hashashin,* or "Hashish-givers," i.e., the *Assassins,* well known from Marco Polo. They formed a secret religio-political sect, strongly in conflict with orthodoxy and even with the Imamate doctrines prevalent in Persia, and seem to have been much concerned with the subjects of man's soul and mind, about which their missionaries had endless discussions with Avicenna's father and brother. To all of their arguments the precocious boy listened carefully, so that, when a certain philosopher called Nātili came to live in Bukhara and was given a lodging in the house of Avicenna's father, the ground was prepared for the boy to acquire a training in philosophy.

Side by side with this and other pursuits Avicenna studied Islamic jurisprudence, thus gaining a taste for legal subtleties and a facility for propounding legal conundrums which were of use to him in argument with his philosophy teacher, to whom he proved himself something of a nuisance, for we read that the master complained to the boy's father that he was wasting time on matters remote from true science. "The fact was," says Avicenna, "that Nātili knew only the externals of philosophy. Of its inwardness he knew nothing."

Of his own rapid advance in mathematics Avicenna says that he read with a master only the first five propositions of Euclid and was then able to work out all the rest for himself. He was even capable of explaining some of them to the master, who had himself been puzzled by the difficulty of the proofs. It is obvious that we are here dealing with a prodigy, and one who was by no means unconscious of his own powers. But I have often remarked in such parts of the East as I have visited that there is not that reticence about personal accomplishments to which we are accustomed here normally. Formal modesty is there regarded as an affectation, and may in fact well be so. Clearly Avicenna did not suffer from it.

After acquiring a good knowledge of the various branches of

philosophy, he decided to study medicine and began reading the extant manuals of physic.

> Medicine [he comments] is not a difficult subject, and in a short space of time, of course, I excelled in it, so that the masters of physic came to read with me, and I began to visit the sick. Consequently there were opened to me the doors to various kinds of treatment which I learnt by experience (or experiment). I was then about sixteen years of age. During the period of hard practice and study which then ensued, I never once slept the whole night through. If a problem was too difficult for me, I repaired to the mosque and prayed, invoking the Creator of all things, until the gate that had been closed to me was opened and what had been complex became simple. Always, as night fell, I returned to my house, set the lamp before me and busied myself with reading and writing. If sleep overcame me or I felt the flesh growing weak, I had recourse to a beaker of wine, so that my energies were restored.

There the narrative of that part of his life described by Avicenna himself ends, as I have said, when he was twenty-one years of age, with the death of his father. The story is taken up by his pupil Juzjāni, who gives details of the very strange and eventful life led by the Shaikh in the years following. Even at the outset of this period Avicenna's fame had spread abroad. While he was stationed at the court of the Khwarazmshah, the ruler of Khiva, south of the Aral Sea, a message came from the famous warrior Mahmūd of Ghazna demanding the presence of a number of scientists and men of learning, amongst whom was Avicenna. He refused the too-pressing invitation, but only at the risk of his life, which his patron helped him to preserve by providing him with a means of escape to Gurgan, on the shores of the Caspian Sea.

In succeeding years he held a number of political posts, all the time keeping his hold on philosophy and medicine. While serving as vizier to the Amir of Hamadan, he somehow aroused the hostility of the army, possibly on theological grounds; the resurrection of the

body being denied by astrologers and physicians. The troops attacked and plundered his house and urged the amir to kill him, so that he found it advisable to go into hiding in a friend's house. There he remained working at his great *Canon* of medicine until, one day, the amir was stricken with colic. Avicenna was summoned from his hiding place, effected a cure and was restored to favour and office. By now also he had begun to compose and dictate the opening chapters of his *Shifa,* a vast and comprehensive work on the general principles of philosophy, metaphysics and logic. Each night there was a gathering of students at his house and to them was read over the material composed during the day, alternated by passages from the *Canon.* When the seminar was over, singers and musicians arrived—the wine not being forgotten—for the entertainment of the company and their learned host.

When this amir who had been Avicenna's employer died, the Shaikh had once again to make a hurried departure to prevent himself being forced into the service of the new ruler. This time he fled to Isfahan, travelling across the desert with a few friends in the disguise of dervishes. Once arrived at his destination, however, he was sumptuously lodged and was able to continue with his various labours, including that on the *Canon.* Since it is on this enormous work that his reputation mainly rests, a word or two may perhaps be said about it here. Some doubt has been cast upon its ever having been used as a text-book of medicine, the suspicion being that it was rather a literary than a scientific effort. Certainly it does seem to contain all the medical learning that had ever been transmitted from Hippocrates onwards. Each Fenn, or Book, is endlessly divided and subdivided under headings, apparently for easy memorizing, and that alone would have made for popularity in the schools both of the East and the West. Moreover, it is full of detail and is said to contain some useful clinical descriptions, especially of diseases of the skin and nerves, all very common in the East. Occasionally there is a piece of original observation, as for example, of an experiment he performed on himself. One day, when he was suffering from hemicrania—which is, of course, migraine—he diag-

nosed as the cause a materies about to descend into what the text calls the "veil" or "partition" of the skull. He thereupon called for crushed ice, which he applied to his head in a cloth. This, he says, strengthened the weak spot in such manner as to enable it to withstand the descending materies and thus led to a cure.

From our point of view, the defects of the *Canon*—apart from its length and general unwieldiness—are its dogmatism and reliance on traditionally accepted theories. Anything not in conformity with them is denounced as empiricism, for which another name is quackery. In illustration of what is meant by traditionalism of this kind I should like to quote a passage from *The Paradise of Wisdom,* a work dating from about a century earlier than the *Canon,* but belonging to the same school. It repeats Hippocrates on the principles of medical treatment, and says:

> The physician must not proceed to treatment until he understands the nature of the disease. When he does that, he must go by opposites. If the disease originates from heat, it must be treated with cold, if from moisture then with dryness, and so forth. If the cause is fear or grief, then the physician must induce tranquillity and confidence in his patient. But first the aetiology of the disease must be understood; only then is it possible to begin treatment.

One of Avicenna's methods of work when confronted with a problem or working at a new section of one of his numerous compositions, was to call for two secretaries and a supply of wine. He would then dictate until the secretaries—and the wine—were exhausted, although he himself remained as full of energy as ever. He never kept copies of his works, so that at his death his books had to be collected from a number of scattered places. Ordinary toil seems not to have affected his tremendous energies. What *did* damage his health was his excessive indulgence in sexual pleasures, which led ultimately to his death. In spite of the busy political and professional existence which he led, he had found time for dissipation, his end probably being hastened by his insistence on treating his ailments according to his own methods. However that may be, he

died on his way from Isfahan to Hamadan in A.D. 1037, when he was about fifty-seven years old. It is not certain at which of the two places he was buried, the more generally accepted tradition being that it was Hamadan. At all events, for some centuries there has been a tomb there to which his name has been attached and was until recently something of a place of pilgrimage. When I visited it in 1919, the guardians of the tomb were mullas or learned men, who used it as a place of study and contemplation and clearly regarded it as having a reputation for sanctity. My arrival happened to take place on what was a holy day in the Muhammadan calendar, and I was not therefore greeted with enthusiasm. When I came next day, however, when the ceremonies were over, all was well.

Alongside the Shaikh's grave and under the same roof was that of Abu Sa'id Daqdāq, the friend who had given him refuge on the occasion of his having aroused the enmity of the amir's army. Several of the mullas there present when I entered pointed out a small circular trough cut in this gravestone, and they assured me that by virtue of Avicenna's proximity it had magical healing properties. They declared that if I drank water which had been poured into the trough, I should be immediately cured of any fever I might be suffering from. I regretted that at the moment my health happened to be remarkably good, and that I therefore was unable to take advantage of the opportunity or to put the matter to a scientific test. However, to compensate for their obvious disappointment, I dropped a couple of coins into the trough and was astounded to see the holy men immediately make a most unholy scramble for them. I took advantage of the confusion to make my exit.

The reason for my having gone there at all was a letter from Sir Wm. Osler, then Regius Professor of Medicine at Oxford, suggesting that when I went to Persia I might report to him on the condition of the tomb. He had heard that it was in a state of dilapidation, and had received a *firman* from the Shah to have it put into good repair. Actually, as far as I could make out, the building was in tolerably good condition, having been partly reconstructed by a

pious and noble lady towards the end of the nineteenth century. It was quite a modest little building of no architectural merit, and so in 1954, in time for the celebrations, it was replaced by a more imposing structure, consisting of a fine tomb-chamber and library, topped by a tall open-work tower designed on traditional lines and so situated as to be visible for miles.

What I have said about Avicenna's personal character shows him to have been a man of extraordinary powers, both mental and physical, with a rare capacity for driving himself and probably others also, and hence making enemies. He seems to have aroused the suspicions of the religious authorities of the day as a sceptic in matters of faith, but he also got a tremendous reputation as a doctor, able to perform almost magical cures. In the Middle Ages in fact, at least in Turkey, he had magical powers ascribed to him, more particularly as a kind of Pied Piper, able to destroy rats and mice. But in the Middle Ages it was enough to have acquired fame of any kind to be accounted a wizard. Even Vergil was declared to have the power of performing miracles.

What Avicenna's status is in the history of scientific progress is difficult to assess. Primarily he was a philosopher, and like others of his kind, took all learning for his province, with medicine as one of its parishes. He was reared under the shadow that Galen had thrown across the centuries and he relied in his practice upon ancient and long accepted dogma, namely the theories formulated in ages long past. Galen's shadow was not greatly lightened by Avicenna, but he appears to have made it easier for his colleagues to make their way about in the gloom. The *Canon* classified and systematized all the Greek medical knowledge that survived, so that part of it at any rate came to be required reading for every medical student in the Islamic world and, in a Latin translation, in Europe too. In its Latin garb, full of strange mutilations of the Arabic original, it was one of the earliest works produced once the European printers began to work.

Avicenna's training was conducted, as I have said, in a climate of ideas about the universe which had not changed since Galen or

even earlier, and, at the risk of covering familiar ground, I must say something about it. The fundamental concept of the physical world, including the human body, was that all matter was composed of four elements: earth, air, fire and water. But there were also four cardinal qualities of nature, namely, heat, cold, dryness and wetness, and each element bears one of these qualities and also possibly one compatible with it, so that an element may be hot, cold, dry or moist; or it can be hot and dry, hot and moist, cold and dry, or cold and moist. Everything in the world, inanimate or animate, is an admixture of the four elements; man himself being composed of them and so also everything which he consumes. As Milton puts it in *Paradise Lost:*

Air, and ye Elements, the eldest birth
Of Nature's womb, that in quaternion run
Perpetual circle, multiform and mix
And nourish all things.

In course of time it became apparent that in between the four elements and the human body as it is, there must exist an intermediate stage, and as early as Galen—late second century A.D.—the theory of the humours was evolved. This declared that from the four elements there were formed four humours, out of which in turn the various parts of the body were composed. These humours were Black Bile, Blood, Choler or Yellow Bile, and Phlegm, each of which more especially represents one of the elements in nature. Thus Black Bile represents Earth, Blood represents Air, Choler represents Fire, and Phlegm, Water. Each humour except Phlegm also has its natural location in the body: Black Bile in the spleen, Blood in the liver, Yellow Bile in the gall-bladder, while Phlegm has no special location, being a by-product of the first "coction" or digestion of food.

These four humours exist in the body in a temperament or complexion, which is a mixture of them all in proper proportions. The word *mizāj,* or mixture, is to this day the word used in Persian and Turkish, as well as sometimes in Arabic, to denote "health." "How

is your noble *mizāj?*" you ask of your friends. Perfect equilibrium of the humours is, however, extremely rare. There is nearly always a preponderance of one or other of the humours, and a man has a special complexion or temperament according to which humour it is. Thus a man with an excess of Black Bile is atrabilious or melancholic by nature; and the signs of it are that he grows black hair on his chest and has a gloomy outlook on life. If Blood preponderates, he is sanguine, fair-haired and lively in disposition; if the gall-bladder is too active and produces too much Choler, then the man is fiery and quick-tempered; whereas an over-abundance of Phlegm, which is cold and wet, makes him phlegmatic, slow and ponderous.

What now is a humour, and how is it created? According to the *Khwarazmiam Treasury,* a Persian medical encyclopaedia dating from about A.D. 1100, it is a moisture circulating in the body. "Its natural location is in the veins and the hollow organs such as the stomach, the liver, the spleen and gall-bladder, and it is produced from the food. Some of the humours are good and some not. Those which are good replace the moistures in the body which are evacuated; the others are useless for this purpose and must be purged out of the body by means of drugs."

The food undergoes a first coction or digestion in the stomach, whereby the more nutritious part of it is converted into chyle, the rest being partly rejected and partly going to form phlegm. The chyle, or chyme, which is the juice extracted from food by digestion, is conveyed to the liver by the portal vein, to which the veins of the stomach and mesentery are tributary, and there, in the liver, it receives a second coction. This separates it into three: a scum or froth which is the Yellow Bile, a sediment which is the Black Bile, and the Blood, which contains the choicest ingredients of the food. The Blood passes on by the Superior Vena Cava to the heart, the more aqueous parts being dismissed to the kidneys for excretion. From the heart it goes for distribution to the arteries, in which there is a third digestion, and so to the various organs, where there is a final coction. Thus the body is built up.

That then is the story of man's framework. But it is not the whole story, for man is also the microcosm. an epitome of the great universe—the macrocosm—and hence he is under the influence of the planets. If born under Mars, he is martial in temperament; if under Mercury, he is mercurial; under Jupiter, he is jovial; if under Saturn, saturnine. For some reason, if it is Venus which happens to be in the ascendant, he is not labelled by the cognate adjective but by something less pointed and derogatory.

The humoral philosophy is by no means outmoded in the Middle East today, and that the stars will have their influence, even in England in the atomic age, is perfectly obvious to anyone who picks up a daily or weekly paper of the more popular kind. In Chaucer's time such ideas were universally prevalent, as you may gather from the Prologue to the *Canterbury Tales,* which contains a delicious thumb-nail sketch of the physician. I should like to read you Nevill Coghill's translation of it.

A Doctor too emerged as we proceeded;
No one alive could talk as well as he did
On points of medicine and of surgery,
For, being grounded in astronomy,
He watched his patient's favourable star, etc.

You will notice the string of authorities enumerated by Chaucer, for the doctor's qualifications were largely a matter of bookwork and theory. Just a little earlier than Chaucer there was published in Egypt a work called *Sign-posts to the Approach to God* or, in other words, *Guides to Piety*. This title, like most others following the Islamic style, gives little indication of the contents of the work, which was intended for the guidance of an officer called the Muhtasib. The title is usually represented by "Censor," but he was in fact an official appointed by the Caliph to superintend public morality and to ensure that the interests of the people were protected. His duties ranged from seeing that wayfarers were not drenched by overflowing gutter-spouts to ensuring that the sick were attended by properly qualified physicians. The book has a

longish chapter devoted to medicine, which, it says, is both a science and an art. It is permitted by the canon laws of the faith because its function is to conserve the health of the body and protect the noble structure of man's frame from disease. The physician, therefore, must be acquainted with the composition of the body and the temperaments of the organs, with the diseases that occur in them, their causes, characteristics and symptoms, with the medicaments which are of value for them and with the ways in which these medicaments are produced. He must also know how to treat diseases in such a way as to bring about a balance between the disease and the remedy, opposing the qualities of the one with those of the other. No person lacking such knowledge is qualified to treat patients, and it is unlawful for any person at all to apply any treatment involving a patient in risk.

From all practitioners the Muhtasib had to exact the Hippocratic oath, making them swear never to administer a noxious medicament or to compound a poison for anyone or to prescribe a drug to bring about abortion or to prevent conception. Doctors must turn their glances away from the women's quarters when visiting a patient, must not reveal a confidence, must never tear aside a veil or venture upon any course forbidden to them. This oath was, of course, a private contract between the members of the medical guild or fraternity, and was not legally binding. Since there was no official system of granting degrees after examination, there could be no conditions imposed before the doctor could practise, except that if called upon by the Muhtasib he had to satisfy that officer. All that was demanded by way of preliminary qualification was apprenticeship to someone already in the business, and that did not necessarily amount to anything very exacting. There is the story of a blind doctor in Baghdad who employed a man to lead him about, inspect urine bottles and generally assist in the practice. Unfortunately the doctor died two months after engaging this assistant, who thereupon immediately opened an office for the treatment of the sick on his own account.

The procedure laid down in this manual for the doctor when

actually called in to visit the sick is instructive. He first had to inquire of the patient what it was that brought on the illness, and the nature of any pain he was suffering. In accordance with the answers he received he had to write a prescription, giving a copy to the relatives. The next day he had to pay a second visit, in order to inquire how the illness was progressing, to examine the urine and question the patient with the object of discovering if he was better or worse. Again he had to prescribe in accordance with what he found, giving the relatives a copy of the new prescription. This process continued until the patient recovered, or else died. If all had gone well, the physician received his fee and an honorarium. If, on the other hand, the patient died, the relatives were told to present themselves before the chief physician officially appointed in each city and lay before him the prescriptions which the doctor had written for the patient. If it was the chief physician's opinion that the treatment prescribed was in accordance with the requirements of science and the art of medicine, with no sign of fault or negligence on the doctor's part, it was his duty to declare that the man's life was ended by the termination of his alloted span. If he was of a different opinion he had to say: "Exact the blood-money for your kinsman from this doctor. He slew him through negligence and lack of skill." "In this excellent way," says the author, "they took their precautions that no one should practice medicine being unqualified and that no qualified doctor should be negligent."

The same work has much to say about oculists and their strict supervision by the Muhtasib. In countries where eye diseases were —and are—so prevalent, his duties were likely to be onerous, if he took them seriously. One of his tasks was to examine practitioners on their knowledge of Hunain ibn Ishāq's work called *Ten Discourses on the Eye,* which dealt with such matters as the structure of the layers of the eye, the number of its humours, the nature of eye diseases and the remedies for them. Apparently there was also a practical examination, in which the persons subjected to it had to show competence in the handling of their instruments,

such as a hook for the removal of growths within the conjunctiva, lancets for bleeding, kuhl (antimony) pencils and other fearsome-sounding tools. Only if the Muhtasib was satisfied could the oculist continue in practice. One class of persons who were on no account to be licensed were the travelling oculists, who, says the author, "go about from place to place attacking men's eyes with their lancets and applying worthless ointments. There is no honesty in them."

Similarly, bone-setters had to be put through their paces and their knowledge of the human frame examined. The size and shape of every bone had to be known, the number being put at 248, so that if one is broken or dislocated it can be restored to its original state. Surgeons too were subject to tests from the Muhtasib. They had to be familiar with Galen's manual on wounds and dressings, and with the anatomy of the human frame, more particularly the muscles, blood-vessels and ligaments, so that these could be avoided when abscesses were opened or haemorrhoids cut out. Each surgeon had to possess a set of instruments, which contained a number of lancets, some with rounded blades, some with square ones and some with the edge at an angle. A variety of knives also had to be included, together with a frontal hatchet, an amputating saw, an ear-piercer, a number of leeches, a packet of dressings and "the olibanum medicament used for stanching blood."

The author of the book has a warning about fraudulent surgeons who secretly insert a bone into a wound and then, when a crowd gathers, extract it with a flourish as a token of their skill in surgery.

A whole chapter is devoted to phlebotomists and cuppers, who must have a reliable knowledge of all the blood-vessels and muscles. Those wishing to qualify in phlebotomy had to practise on beetroot leaves, or rather on the veins of those leaves. No slave could be bled without his master's permission, nor a minor without permission of his guardian; and the operation was forbidden for women in certain conditions. Bleeding had to be performed only in public, for obvious reasons (? murder); and with a sharp instrument, and only when the operator was in a state of mental

calm. A list is given of the veins which may be bled in the head, hands, body and feet, the advantage to be derived in each case being specified. Cupping is declared to be less dangerous than phlebotomy—the test of the operator's skill being whether he inflicts pain when he makes his scarification.

The phlebotomist also undertook circumcisions, male and female, and carried the necessary instruments, consisting of a razor and a pair of scissors. The manual lays down the penalties incurred if the operation is badly performed and the patient suffers injury or dies.

To return to Avicenna and his methods of treatment. In his system of diagnosis, he lays great emphasis on the pulse and on the inspection of the urine. According to him, each pulsation consists of four factors: expansion, pause, contraction, pause. There are ten kinds of pulse, determined (1) by the extent of the expansion —short, long or intermediate; (2) by the quality of the impact on the fingers of the observer—strong, weak or intermediate; (3) by heat and cold, etc., etc.

As far as the urine was concerned, the chief points to be noted were the amount, colour, consistency and sediment.

Like his predecessor, the author of the *Paradise of Wisdom*, Avicenna was greatly concerned with the psychological factors in disease, and various tales are told of his skill in identifying the causes which have given rise to melancholia in various sufferers. But instructions to the physician in dealing with cases are clearest in the *Paradise of Wisdom* itself. This lays it down that when dealing with a patient many details must be ascertained about him, such as his temperament, age and habits, both when he is active and when he is at rest. If he is a craftsman, the circumstances of his employment must be known, as, for example, whether he works in heat or near water; and it is important to know where he was born, whether in mountainous country or on the plains, in the desert or in cultivated land. Also significant is the medical history of his parents. With regard to treatment, use is second nature, and those things are good for a man to which he is accustomed. "Thus,"

says the author, "I have seen numbers of people from Bahrain and the marshes of Iraq who fell ill when they were entertained on wholesome food and sweet water, but recovered when they went back to a diet of fish and dates and had fetid water to drink."

The same author has a chapter on Fatness and Leanness, in which he discusses their causes. Fatness, he says, may be due to eating coarse food, to lack of exercise, to sleeping on a soft bed, to infrequent sexual congress, to failure to visit the hot baths often enough and to stay there long enough, to sleep after meals and to the practice of vomiting before meals. This last works by emptying the stomach and stimulating it to more active hunger. "But I have observed," he remarks, "that the most potent causes of fatness are ease and comfort, wealth and social importance."

That observation throws a good deal of light on the economic value of a good position in society. "As for those things which emaciate the body," the author continues, "they are hot, dry foods which cause desiccation, excessive toil and sleep before meals. But I have observed that the most powerful causes of emaciation are heavy labour, sleeplessness, grief and poverty."

So far as remedies were concerned, there was as a rule, as I have said already, a routine application of the law of opposites; a hot disease demanded a cold remedy, and vice versa. To make sure, however, most medicines were of the blunderbuss variety, filled with all sorts of ingredients of which one or other would hit the target. In any event, treatment was applied on trust and a prescription usually ended with the formula: "And this will prove beneficial, if Allah will." Obviously, of course, each country and place had—and has—its own traditional remedies for local afflictions. Thus Sir John Chardin, the famous seventeenth-century traveller in Persia, advised anyone going there who wished to ward off or cure spring colds to eat plenty of melons of the variety known as *garmek,* or "little hot" ones. He says the Persians in the spring ate a matter of ten or twelve pounds a day of it, looking upon it as "a great refresher and cooler of the blood, and if a man be emaciated, it will restore him again and make him grow fat."

To support his recommendation, Chardin tells the story of two Arabian physicians who came to Isfahan just at the melon season and, seeing the bazaar full of this kind of fruit, said to each other, "Let us go farther on; don't let us stay here. There's nothing for us to do in this place. These people have a remedy for all distempers."

I should like to end this talk with the advice given to a prospective physician by a prince who was about contemporary with Avicenna and with whose family he had had contacts. This gentleman was anxious to provide his son with guidance in every emergency which might arise in the unsettled times in which they lived, and in his book, the *Qabus-nama,* a kind of "Mirror for Princes," he imagined the possibility of the young man's being reduced to earn his livelihood by the practice of medicine.

"There is no living to be made out of it, my son," he says, "without some manipulation, quackery or bolus-mongering, in the same way that there is no money to be got from astrology, fortune-telling or the interpreting of omens, so long as these professions are without the accompaniment of some embroidery, whether solemn or farcical." All the same, once you embark on a career as a physician, if you wish to gain experience and a reputation, you must experiment freely. But you had better not choose people of high rank or political importance for your subjects. To gain competence, you must see a great deal of service in hospitals, where cases of all sorts should pass under your hands, and where you should actually see for yourself what you have read about in the text-books. With such training, no disease, however rare, will present you with any difficulty, and diseases of the internal organs will be no mystery to you.

When you visit a patient in his house, you must be clean in person and dress and agreeably perfumed. The expression of your countenance should be pleasant and you should go only when you are untroubled in spirit. The physician's encouraging words increase the potency of the warmth inherent in a man's natural temperament. Never try to cover your failures by charging the patient with

not having obeyed your instructions, and never exact a promise of obedience, for, to take an instance, the glutton will never agree to have his diet restricted. In short, the exhortation to the physician is to take responsibility himself.

I have ranged rather freely under cover of the title of this lecture, in which I have gone back to the dark ages of medicine. It is only in those shadows that a layman like myself dare venture, but I hope I have thrown a faint ray of light on one famous figure who lies there.

Ernest A. Moody

LAWS OF MOTION IN MEDIEVAL PHYSICS*

Philosophers have discussed motion ever since the days of Thales (*ca.* 585 B.C.), seeking to explain it in terms of unchanging eternal causes. Modern physics has been less ambitious, but more successful, through seeking only to discover invariant functional relations between certain measurable factors involved in motions. These factors are, fundamentally, *distance, time,* and *mass.* As occurring in the general laws of motion, however, these factors appear in the form of differential expressions such as *velocity, acceleration, force, momentum,* and *kinetic energy,* representing elementary displacements of mass particles in infinitely small lapses of time. Without the procedures of differentiation and integration provided by the calculus, generalized laws of motion, exhibiting the invariant relations underlying the enormously complex and varied phenomena of movement and change, are scarcely attainable. The history of mechanics, or of man's effort to bring movement and time into the domain of mathematical order and intelligibility, has been in large

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measure the history of man's progress toward discovery and use of the infinitesimal method.

Modern mechanics is generally said to have been founded by Galileo (1564-1642). He is credited with the first clear and conscious enunciation of two fundamental principles of mechanics. One of these is the principle that a *force,* and in particular the force that we call "gravity," is to be measured by the *acceleration* of the body on which it acts, and not by the simple velocity of the body. The second principle, essential as a means of determining the value of a force from measurements of finite displacements of bodies through measurable periods of time, is the kinematic law which relates distances traversed to time elapsed in uniformly accelerated movement. These two basic principles are expressed in the familiar equations of our physics books: (1) $F = m \cdot a$, and (2) $s = \frac{1}{2}a \cdot t^2$. In developing these laws of motion Galileo acknowledged no predecessors or sources. The only theory of motion of which he took account was that of Aristotle, and his whole effort was to refute Aristotle's theory.

Until the present century, historians of science have taken it for granted that Galileo did not have any predecessors of importance, and that the Aristotelian dynamics had been uncritically accepted throughout the entire medieval period. Due in large measure to the pioneer historical studies of Pierre Duhem,[1] it is now known that this assumption was mistaken. The Middle Ages developed a mechanics of its own, in criticism of that of Aristotle; and this mechanics contained many ideas and methods, as well as some of the basic laws of motion, that entered into the structure of the physics of Galileo and Newton. We shall here consider the contributions made by fourteenth-century mathematicians and physicists who worked at the universities of Oxford and of Paris, which have direct bearing on the development of the two basic "laws of motion" already mentioned. The kinematic contribution was made first, at Oxford, and the development of the dynamic

[1] Duhem, Pierre. *Études sur Léonard de Vinci,* 3 vols. Paris: 1906-13.

analysis took place only slightly later at Paris. In both cases, the starting point of the new formulations was dissatisfaction with the treatments given by Aristotle and his commentators to the problem of local motion. The Aristotelian doctrines were not branded as false, but they were criticized on grounds of obscurity, inadequacy, or inconsistency. The attempts to remedy these defects nevertheless turned out to undermine the whole Aristotelian formulation of the problem, and to replace it with a radically new mechanics.

To understand the medieval contributions we must examine the basic law of motion proposed by Aristotle. In the seventh book of his *Physics* he set forth three rules governing the proportions of distance, time, motive power, and resistance, in rectilinear displacements of bodies acted upon by an external mover. His law may be expressed, in general form, by the statement that the ratio of distance traversed to time elapsed varies directly with the motive power and inversely with the resistance. Letting F represent force, or "motive power," R the resistance, s the distance, t the time, and k a constant depending on the metrical units chosen, Aristotle's law takes this form: $F/R = k \cdot s/t$.

An important restriction is made on this law by Aristotle; namely, it applies only within the class of cases where the motive power F is greater than the resistance R. Where force is equaled by the resistance, there is no movement. This restriction indicates that Aristotle conceived resistance in the manner of an opposed force, as would be exemplified in the case of two weights on opposite arms of a balance, the heavier being the "mover" and the lighter one the "resistance."

A second point to be noted is this: Aristotle does not treat the ratio s/t as a differential rate of displacement in each infinitely small part of the time of the motion; he interprets t as representing the whole time of the movement, and s as representing the whole distance traversed. This leaves open the question of whether, *within* that period of time, the body is moved at a constant velocity, or at a constantly changing velocity. Presumably Aristotle understood such motions to be at constantly changing velocity, since he held

that rectilinear local motions are either "natural" or "violent," and that both kinds are normally at constantly changing speed.

The principal obscurity in Aristotle's law is offered by the term "resistance." In this he includes friction, the density of the medium through which the body is moved, and, where the movement runs counter to the "natural" motion of the body, its heaviness or lightness relative to the medium in which it is moved. Mass, in the modern sense as resistance to acceleration, is not distinguished from the other types of resistance, though it is perhaps understood in a vague way as constituting the resistance offered to the motion by the corporeal medium.

It is clear that Aristotle's law, though plausible as a formulation of the special case of weights connected by a lever or pulley arrangement, is a gross oversimplification of the problem of the local motions of bodies in general. It presents insuperable difficulties when applied to the cases of free fall of heavy bodies, or of the movement of projectiles. More particularly, in its neglect of the whole question of how moment-to-moment velocities are related *within* the whole time of the movement, Aristotle's law permits of no consistent application to all kinds of local motions. The radical shift from Aristotelian dynamics to modern dynamics, initiated in the early fourteenth century, involved two essential steps: (1) A kinematic analysis in which motions at constant velocity are distinguished from motions at changing velocities, requiring the concept of "instantaneous velocity" and a method of differentiation and integration of velocities as functions of time; (2) a reinterpretation of the concept of "resistance," whereby it is conceived as resistance to acceleration, entailing a reinterpretation of "motive power" as that which acts to *change* the velocity of a mass. Let us now examine the beginnings of these two developments in the early fourteenth century.

II

The leading mathematician of the early fourteenth century was Thomas Bradwardine (1290-1349), who was active as a teacher at Merton College, Oxford, up to the year 1335. Merton College was the leading center of mathematical studies in all of Europe during this period. It was here that John Maudith produced the first Western treatise on trigonometry in 1310. Bradwardine, who had himself done important work in pure mathematics, wrote a treatise in the year 1328 in which he attempted to employ a strictly mathematical method in the field of dynamics. His treatise was entitled "On the Proportions of Velocities in Motions." [2] In a brief preface, he stated that although philosophers had disputed about motion for centuries, and had asserted that velocities are in some way proportional to motive powers and resistances, none of them had shown, by mathematical means, just what kind of proportionality is involved.

In his first chapter Bradwardine reviews the Euclidean theory of proportion, and makes evident the vast difference between arithmetic and geometric proportionality. In his second chapter he examines and criticizes several "erroneous" theories or laws relating velocities to forces and resistances, and in his third chapter he sets forth the "true theory." Of the theories criticized, only two are of interest. One of these is the law of simple proportionality, which we have attributed to Aristotle and which is represented by the formula $F/R = k \cdot s/t$. The other is a modification of the Aristotelian law derived from the Arab philosopher Ibn-Badga (Avempace), which may be represented by the formula $F - R = k \cdot s/t$. We shall here consider only Bradwardine's criticism of the Aristotelian law and the reformulation he proposes.

[2] Bradwardini, Thomae. *Tractatus de proportionibus velocitatum in motibus,* Paris: De Maruef, 1495. A modern edition of this work, with an English translation, is being prepared by H. Lamar Crosby, Jr., of Hollins College. [Published Madison, University of Wisconsin Press, 1955.—Ed.]

Bradwardine accepts two basic assumptions made by Aristotle as conditions which must be satisfied by the general law of motion. First, it is postulated that motion occurs only if the motive power is greater than the resistance. Second, it is assumed that the velocity has some kind of functional dependence on the ratio of the motive power to the resistance. Bradwardine shows that if this function is supposed to be one of simple proportionality, the first assumption cannot stand. For, if a certain velocity is produced by some ratio of F to R, say, a ratio of $3/1$, then if we divide that velocity by a number equal to this given ratio (or by 3), it will follow on Aristotle's law that this second velocity is produced by a ratio of equality between F and R. But it was postulated that when motive power and resistance are equal, there is no velocity at all, but a state of equilibrium.

In order to eliminate the contradiction involved in the formula of simple arithmetic proportionality, Bradwardine reformulates the law as an exponential function in which the integral series of velocities is correlated with an exponential series of values of the ratio F/R. Thus, if a given velocity arises from a certain ratio F/R, such as is greater than the ratio $1/1$, twice that velocity will be produced by a ratio $(F/R)^2$, three times the velocity by a ratio $(F/R)^3$, one half the velocity by a ratio $\sqrt{F/R}$, and so on. Bradwardine's law, therefore, would be expressed in modern notation as a logarithmic function of this form: $V = \log_k(F/R)$, where the log base k is a constant such as is equal to F/R when the velocity $V = 1$. Since the logarithm of $1/1$ is zero, the first postulate is satisfied, that where force and resistance are equal, velocity is zero.

This law of motion is erroneous under any recognized modern interpretations that can be given to the factors of motive power and resistance. Bradwardine himself makes no attempt to give empirical meanings to these factors, his entire concern being that of finding a mathematical function which satisfies the two basic postulates accepted from Aristotle, and which is internally consistent and wholly general. But, in carrying out this task, Bradwardine introduced two new ideas of great historical significance. First, he

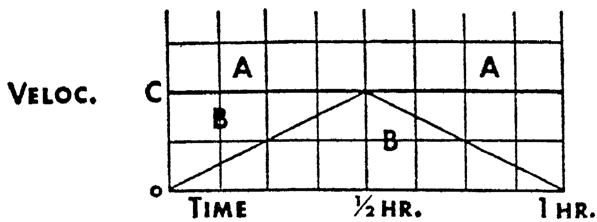
introduced an exponential function into the statement of a law of physics, for the first time in history; and, in view of the fact that nearly all our modern mechanical laws, in their algebraic formulations, involve exponential functions, this innovation must be considered important for later developments. Second, in his discussion of his law and of objections to it, Bradwardine makes it clear that his law is stated for *velocities* in the differential or "instantaneous" sense, and that it is not intended to express the proportion of total distances traversed in the whole time of the motions compared. Bradwardine calls the differential velocity the "quality" of the motion, distinguishing it from the integral sense which depends on the length of the time of the motion, and which he calls the "quantity" of the motion. He makes this distinction in discussing the objection that two bodies might traverse equal distances in an equal time, even though they are not moved at the same velocity during any finite part of the time. Such would be the case, for example, if one body were moving at constant velocity while the other was uniformly accelerated from rest to a terminal velocity twice as great.

It was among Bradwardine's pupils and younger colleagues at Merton College that these new ideas received their fruitful development. Between the years 1330 and 1340, three of these Mertonians, John Dumbleton, William Hentisberus, and Richard Swineshead, wrote treatises in which the concept of instantaneous velocity was given precise definition and applied in an exact and substantially correct analysis of uniformly accelerated movement. We may quote from Hentisberus' treatise *On Local Motion* to exhibit the accurate way in which these ideas were developed.[3] After stating that the movement of a body as a whole is that of its most rapidly moving point, Hentisberus writes as follows:

[3] Hentisberus, Gulielmus. *Tractatus de motu locali,* in a collection of treatises by Hentisberus and others entitled *Gulielmi Hentisberi Tractatus de sensu composito et diviso,* edited by Joannes Mappellus of Vincenza, printed at Venice in 1494. The texts here translated occur on folios 37 recto to 40 verso of this edition.

Of local motions, that motion is uniform in which an equal distance is continuously traversed with equal velocity in equal parts of the time. . . . But in non-uniform local motion, the velocity at any assigned instant is determined by the path which *would* be described by the most rapidly moving point if, in a period of time, it were moved uniformly at the same velocity with which it is moving in that assigned instant, whatever instant be assigned. . . .

For it is not required, in order that any two points . . . be moved at equal velocity, that they should traverse equal spaces in an equal time; but it is possible that they traverse unequal spaces in whatever proportion you please. For suppose that point *A* is moved continuously and uniformly at *C* degrees of velocity, for an hour, and that it traverses a distance of two feet. And suppose that point *B* begins its motion from rest, and in the first half of that hour accelerates its velocity to *C* degrees, and in the second half hour decelerates from this velocity to rest. It is then found that at the middle instant of that whole hour, point *B* will be moving at *C* degrees of velocity, and will fully equal the velocity of the point *A*. And yet, at the middle instant of that hour, *B* will not have traversed as long a line as *A*. . . [Fig. 1].



From this it clearly follows that such a non-uniform or instantaneous velocity is not determined by the distance traversed, but by the distance which would be traversed by such a point if it were moved uniformly over such or such a period of time at that degree of velocity with which it is moved at that assigned instant.

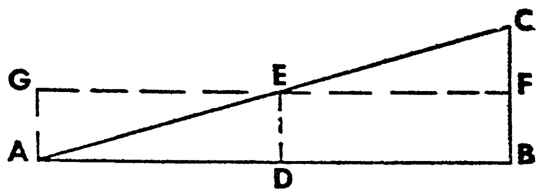
After defining a uniformly accelerated motion as one in which an equal *increment* of velocity is acquired in each equal part of the time, Hentisberus raises this question: If one body is uniformly

accelerated from rest to a certain terminal velocity, in a certain time, at what velocity would another body have to move, if it were moved at constant velocity for that same length of time, in order to traverse the same distance traversed by the accelerated body? Hentisberus' answer is the one that we give now: "The moving body which is accelerated uniformly during some assigned period of time, will traverse a distance exactly equal to what it would traverse in an equal period of time if it were moved uniformly at its mean degree of velocity."

Where the acceleration is from rest to some assigned terminal velocity, Hentisberus continues, the mean degree will be one half of that terminal velocity. This yields the equation $s = \frac{1}{2}v \cdot t$, where s represents distance, v the terminal velocity, and t the length of the time. Since the terminal velocity v is obtained by multiplying the rate of acceleration (symbolized by a) by the time-length t, we may substitute $a \cdot t$ for v, in Hentisberus' equation, and obtain the familiar formulation of the kinematic law of uniformly accelerated motion: $s = \frac{1}{2}a \cdot t^2$. Hentisberus makes his meaning concretely evident by this corollary: "When the acceleration takes place uniformly, from rest, the distance traversed in the first half of the time will be exactly one third of the distance traversed in the second half of the time."

Extending this relationship to subsequent equal divisions of the time, we obtain Galileo's formulation of the law of uniformly accelerated motion, according to which the spaces traversed in equal successive parts of the time will be related as the series of odd numbers. The precision and clarity of Hentisberus' discussion leave no room for doubt of the fact that the kinematic law of uniformly accelerated motion, which was one of the cornerstones of Galileo's mechanics, was clearly understood and clearly stated in the early fourteenth century. To prove it, in what would be considered an adequate manner by present-day standards, requires the powerful tool of the calculus, not available prior to Newton's time. But this proof was approached, with clear consciousness of the infinitesimal problem involved, by these fourteenth-century "calculators" of

Merton College. Their proofs are highly complex, but essentially sound. A simpler form of proof, by use of graphic representation through geometrical figures, was developed later in the fourteenth century by Nicole Oresme,[4] and it was this geometrical demonstration that Galileo employed in 1610 or later.



Oresme represents the time in which the motion occurs by a horizontal line, and he represents the velocity of the motion, at any given instant, by a vertical line erected on the horizontal (Fig. 2). If the motion is at constant velocity, it will be represented by a rectangle; if it is uniformly accelerated from rest, it will be represented by a right triangle. Oresme then supposes that the distance traversed in the whole time is represented by the area of the figure, since this area is an integral, or sum, of the infinitely small displacements corresponding to the instantaneous velocities at each instant of the time. To prove Hentisberus' equation, $s = \frac{1}{2}v \cdot t$, Oresme needs only to show that the area of the triangle ABC (representing the distance traversed in the accelerated motion), is equal to the area of the rectangle $ABFG$ (which represents the corresponding uniform motion). But it is easily proved, by elementary geometry, that the triangle AGE is equal to the triangle EFC, and that ED, bisecting the base AB at its mid-point D, is equal to FB and consequently equal to $\frac{1}{2}BC$. The step-by-step development of Oresme's proof, as also of the algebraic proofs offered by the Oxford calculators, indicates that these men were keenly aware of the implica-

[4] Oresimus, Nicolas. *Tractatus de uniformitate et difformitate intensionum.* Part III, chap. 8. This work exists only in medieval manuscripts: we have used *Ms. lat. 7371* of the Bibliothèque Nationale, Paris, fols. 213 recto to 266 recto. The treatise is quite fully analyzed by P. Duhem, *op. cit.*, III, 375-98.

tions of their methods of integrating "instantaneous velocities," as involving fundamental problems of continuity and convergence to limiting values.

III

What is perhaps most striking about the work of the Oxford calculators is their complete indifference to the empirical interpretations of which their highly developed kinematic analyses were susceptible. Their attitude was wholly abstract, their interest in motion being that of mathematicians to whom the constantly changing functional dependence of space traversed on time elapsed presented an interesting problem for abstract analysis. It was only at Paris, during the middle years of the fourteenth century, that the kinematic analysis of uniformly accelerated movement, with its concepts of instantaneous velocity and of uniform acceleration, received a dynamical and empirical interpretation. This second fundamental contribution to the development of modern mechanics was largely made by Jean Buridan, who taught on the Parisian Faculty of Arts from 1328 to 1358.

Buridan's starting point was a criticism of Aristotle's explanation of the movement of projectiles. Aristotle had assumed that, if a body is moving in a direction contrary to that of its "natural" motion, it must necessarily have some body in contact with it which is pushing or pulling it in this direction. Yet if a stone is thrown into the air it continues to move upward after the thrower is no longer in contact with it. Rather than abandon his general principle, Aristotle tried to explain this by the theory that the air, initially compressed by the violent movement of throwing, follows after the stone and keeps pushing it upward for a time. This feeble theory was a cause of much discussion and criticism during the fifty years prior to Buridan's time, and various alternative solutions were suggested. Buridan, after refuting Aristotle's theory by a number of empirical arguments, offers his own solution in these words:

> The mover, in setting the projectile in motion, gives to it a certain *impetus,* or a certain energy (*vis*), by which that projectile keeps moving in the direction in which the mover set it in motion. . . . The more rapidly the mover moved it, the greater the *impetus* which was given to it; and it is by that *impetus* that the stone is moved after the thrower ceases to move it. But by the resistance of the air, and by the gravity of the stone (which tends in a direction contrary to that in which the stone tends in virtue of its *impetus*), this *impetus* is continuously diminished, so that the movement of the stone becomes continuously slower; and the *impetus* is finally decreased to the point where the gravity of the stone exceeds it and causes the stone to fall downward toward its natural place. . . .
>
> If then it is asked why I throw a stone further than a feather, and an iron weight (of a size proportionate to my hand) further than a wooden one of the same size, I say that the cause of this fact is that the reception of all natural forms and conditions in matter, is determined according to the matter. Hence, the greater the *quantity of matter,* the greater the degree of *impetus* that the body can receive. Now in the dense and the heavy, other things being equal, there is more primary matter than in the rare and the light; consequently the dense and the heavy receive a greater *impetus,* just as iron receives more heat than an equal volume of water or wood. A feather, however, receives *impetus* in such a small degree that this *impetus* is quickly overcome by the resistant air.[5]

The concept of *impetus,* as defined and used by Jean Buridan, represents a new factor in the analysis of motion, not involved in the Aristotelian dynamics. And the concepts in terms of which it is defined likewise are new—namely, that of "quantity of matter," and that of velocity (here taken in its "qualitative," or differential, sense). Although the "quantity of matter" of a body is said to be *proportional* to its weight or gravity, it is distinguished from weight, being taken as a scalar quantity and not a vector quantity. Thus it

[5] Buridanus, Johannes. *Quaestiones super octo libros Physicorum Aristotelis.* Book VIII, Question 12. Edition of Johannes Dullaert of Ghent, printed at Paris, 1509; fol. 120 verso. A similar but shorter treatment of the same subject is given by Buridan in his *Quaestiones de caelo et mundo,* edited by E. A. Moody. Cambridge, Mass.: 1942, pp. 240-43.

functions, in the definition of impetus, exactly as *mass* does in the definition of *momentum;* and impetus is here defined by the product of mass and velocity, so that it is equivalent to what we call momentum in Newtonian mechanics.

More significant is Buridan's further statement, that impetus is an "enduring reality," a condition that remains constant except insofar as gravity or other forces operate to increase or diminish it. Buridan states this very explicity, in these words: "This impetus would endure for an infinite time, if it were not diminished and corrupted by an opposed resistance or by something tending to an opposed motion." [6]

These statements of Buridan obviously suggest Newton's first law of motion, according to which a body continues to move with whatever velocity it has, except insofar as it is acted upon by a force. Although Buridan may not have realized the immense import of this "principle of inertia" for the science of mechanics as a whole, he seems to have recognized it, and to have used it with conscious intent, in his explanation of projectile motions. But he went further than this, by introducing the concept of impetus into the analysis of the uniformly accelerated movement of freely falling bodies, with the result that the force of gravity is defined as that which continuously increases the impetus of the body on which it acts.

> It must be imagined that a heavy body acquires from its primary mover, namely from its gravity, not merely motion, but also, with that motion, a certain *impetus* such as is able to move that body along with the natural constant gravity. And because the *impetus* is acquired commensurately with motion, it follows that the faster the motion, the greater and stronger is the *impetus*. Thus the heavy body is initially moved only by its natural gravity, and therefore slowly; but it is then moved by that same gravity, as well as by the *impetus* already acquired, and thus it is moved faster . . . and so it is continuously accelerated always, to the end.[7]

[6] Buridanus, Johannes. *Quaestiones in Metaphysicam. Aristotelis.* Book XII, Question 9; edition of Iodocus Badius Ascensius, Paris: 1518; fol. 73 recto.
[7] Buridanus, Johannes. *Quaestiones de caelo et mundo,* edited by E. A. Moody. Cambridge, Mass.: 1942, p. 180.

Although Buridan's manner of expressing this dynamical analysis of gravitational motion is somewhat crude, the fundamental principle is nevertheless recognized and stated, that the effect of gravity (just as of other forces such as air resistance) is to *change* the momentum of a body continuously with the time. Thus the modern conception of *force,* as measured by the rate of acceleration of a body and by its mass, or by the rate at which it changes the momentum of a body, is applied by Buridan to the analysis of freely falling bodies and to the definition of gravity. Just as Newton's second law of motion follows from his first law, so Buridan's conception of gravity as a force whose effect is to change the momentum of the body on which it acts follows as a consequence of his definition of impetus as an "enduring condition" measured by velocity and "quantity of matter." It seems likely that Buridan, who was familiar with the kinematical analyses emanating from the Oxford school, was guided in this new dynamical analysis of the movement of projectiles and of freely falling bodies by the mathematical patterns established in the abstract analysis of uniformly accelerated motion. Buridan did not, however, bring his own dynamical analysis of gravitational motion into explicit association with the kinematic law relating distance traversed to time elapsed. This was done by Domenicus Soto, in a work published at Salamanca in 1572.[8] But Soto's entire discussion of motion, in both its kinematic and dynamic aspects, is wholly dependent on the works of the Oxford calculators and of the Parisian school of Jean Buridan.

In the foregoing sketch we have picked out the two developments of fourteenth-century mechanics that stand at the beginning of the great shift from Aristotelian physics to the modern Galilean-Newtonian mechanics. These fourteenth-century contributions are sufficient to show that modern physics, and the two basic laws of motion represented by $s = \frac{1}{2}a \cdot t^2$ and by $F = m \cdot a$, grew from earlier beginnings some three hundred years before Galileo

[8] Soto, Domenicus. *Super octo libros Physicorum Aristotelis.* Salamanca: 1572, fol. 93. Quoted by P. Duhem, *op. cit.*, III, 558-60.

"founded" modern physics. To what extent this fourteenth-century tradition influenced Galileo and other seventeenth-century physicists in their work is a question that cannot be answered until a great deal more historical evidence has been uncovered and examined. But it may at least be said that the background of ideas within which the seventeenth-century physicists worked stemmed in large measure from the later Middle Ages and undoubtedly influenced the direction in which modern physics developed.

The deficiencies of fourteenth-century mechanics were very great, and sufficient to prevent any fullfledged development of the fertile ideas and keen mathematical analyses which are to be credited to Buridan and to the Oxford calculators. The medieval interest in physics was dialectical and abstract, rather than experimental. No real effort was made to test or confirm the theories proposed, by observation and experiment; the formulas devised to express the relations of dynamic factors in motions were given no operational interpretations by means of procedures or units of measurement. Even the mathematical developments, which clearly foreshadow the functional and differential methods of modern mathematics, could scarcely be carried to any fruition until symbolic notations adequate to these methods had been developed. Perhaps the primary historical significance of the fourteenth-century effort to achieve a quantitative and functional analysis of motion is that it made evident the need for a new kind of mathematics, and by its crude attempts to carry out differentiations and integrations of velocities showed what form this new mathematics would have to take. This in itself was a magnificent achievement, even though it required more than three hundred years for the seeds planted in the fourteenth century to grow to maturity.

J. L. E. Dreyer

MEDIAEVAL ASTRONOMY*

The study of Mediaeval Cosmology and Astronomy has hitherto not attracted many students. This is perhaps partly due to the fact that the period in question is one of stagnation, during which astronomy made absolutely no progress in Christian countries, while the high state reached by science at Alexandria had gradually to be won back. But the chief reason of the neglect is that many interesting writings from the Middle Ages have never been printed and have therefore to be looked for among the manuscript treasures in great libraries, particularly in the Bibliothèque Nationale at Paris. The great work of M. Pierre Duhem, *Le Système du Monde, Histoire des Doctrines cosmologiques de Platon à Copernic,*[1] is therefore particularly welcome, and it is quite up to the high standard of excellence of his previously published historical works, *Études sur Léonard de Vinci* and *Les Origines de la Statique*. So far, five volumes of more than five hundred pages each have been published, and it is remarkable that so great a work should have appeared in France during the terrible struggle in which that

* Reprinted from *Studies in the History and Method of Science,* Vol. II, edited by Charles Singer (Oxford, 1921), pp. 102-20, with the permission of the Clarendon Press.

[1] Paris, A. Hermann et Fils, 5 vols., 1913-17.

country was then involved. The five volumes reach to the beginning of the fifteenth century; and how far the work will be continued may be doubtful, as the death of the author was announced in 1916. It was stated in the Paris Academy in December 1916 [2] that the work was to have been completed in ten volumes, and that the fifth and sixth had been entrusted by M. Duhem's daughter to the Academy. The fifth volume appeared in 1917. But even if not completed according to the original plan, the work will be of exceptional interest on account of the great number of manuscripts which M. Duhem has examined, and from which he has given lengthy extracts.

The work is (so far) divided into three parts. "Greek Cosmology" occupies the first volume and four-fifths of the second one. "Latin Astronomy in the Middle Ages" reaches to the middle of the fourth volume, and is followed by "The Rise of Aristotelism," which at the end of the fifth volume is carried as far as Thomas Aquinas. As Greek Cosmology has been dealt with in two works published in England during the last fifteen years, that part of M. Duhem's work does not call for special notice in this place. Neither do the chapters of Part I dealing with Arabian astronomy (which the author considers as a mere continuation of Greek science) contain anything new. As a rule, the author shows a thorough acquaintance with the literature of his subject, though we have in a few cases failed to find references to important works, such as the *Liber Jesod Olam* of Isaac Israeli or *Le livre de l'Ascension de l'esprit* of Abu'l Faraj. It is particularly the chapters dealing with Latin Astronomy in the Middle Ages which will be of permanent value, as they give accounts of many manuscript treatises never before described.

The last great astronomer of the Alexandrian school, Claudius Ptolemy (about A.D. 140), wrote a complete compendium of ancient astronomy as finally developed by Hipparchus and himself. During the 270 years which had elapsed since the days of Hipparchus astronomy had certainly not stood still, but we know next

[2] *Comptes rendus,* December 18, 1916.

to nothing about the progress made, as Ptolemy gives very little historical information. The details given by Pliny about the situations of the apsides of the eccentric orbits of the planets show, however, that Ptolemy had more than the work of Hipparchus to build on. Pliny's source was no doubt the book *De novem disciplinis* by M. Terentius Varro, which is unfortunately lost. It seems to have been a sort of condensed encyclopaedia, and was superseded by writings of a similar kind from the fourth and fifth centuries which have come down to us. These are, the commentary to Plato's *Timaeus* by Chalcidius, the commentary to Cicero's *Somnium Scipionis* by Macrobius, and the encyclopaedic book *De nuptiis Philologiae et Mercurii* by Martianus Capella. Being written in Latin they were more readily accessible to Western readers than the lengthy Greek works of Proklus and Simplicius; and during the first half of the Middle Ages they were, together with Pliny's *Natural History,* the only books from which some knowledge of Greek science might be derived by students in the West.

The first feeble light after the dark night of the patristic writers came from Isidore, Bishop of Seville, who died in 636. When dealing with dangerous topics such as the figure of the world and the earth he does not lay down the law himself, but quotes "the philosophers" as teaching this or that, though without finding fault with them. In this manner he repeatedly mentions that heaven is a sphere rotating round an axis and having the spherical earth in its centre. The water above the firmament mentioned in the first chapter of Genesis had of course to be brought in, and Isidore states that the Creator tempered the nature of heaven with water, lest the conflagration of the upper fire should kindle the lower elements. Isidore gives as his authorities Hyginus (author of a versified description of the constellations), Clement of Alexandria, and the patristic writers, but does not mention Pliny, so that it is no wonder that his knowledge is very fragmentary.

The Venerable Bede, who lived a century later (he died about 735), was better informed. The contents of his treatise *De Natura Rerum* are taken from Pliny, often almost verbatim; and the

spherical form of the earth, the order of the seven planets circling round it, the sun being much larger than the earth, and similar facts are plainly stated. But the water around the heaven and the usual explanation of its existence could not be kept out of the book, even though Pliny did not mention it and though Bede had stated that the earth was a sphere. Another and much larger book on chronology (*De Temporum Ratione*) shows a fair knowledge of the annual motion of the sun and the other principal celestial phenomena. It is deserving of notice that Bede from his study of Pliny and from personal observation knew a good deal about the tides, and was the first to show that the "establishment" of a port (or the mean interval between the time of high water and the time of the moon's previous meridian passage) is different for different ports. But the sphericity of the earth was still rather unpopular among ecclesiastics, and even in the first half of the ninth century Hrabanus Maurus, Archbishop of Mainz, thought it best to say nothing about it. He merely says that the earth is in the middle of the world, and tries hard to reconcile the roundness of the horizon with the four corners of the earth alluded to in Scripture. His statement that the heaven has two doors, east and west, through which the sun passes, also looks as if his point of view was much the same as that of the patristic writers. But he was the last prominent author of whom this may be said, and from about the ninth century the spherical figure of the earth and the geocentric system of planetary motions were reinstated in the places they had held as facts ascertained with certainty among Greek philosophers twelve hundred years earlier.

Among the writers of the ninth century who paid any attention to the construction of the Universe, the most remarkable was John Scotus Erigena. In his great work *De Divisione Naturae* he shows that he is acquainted with Chalcidius and Martianus Capella, and for the first time we perceive a very curious influence which these rather inferior writers exercised throughout the Middle Ages. In the fourth century B.C. Herakleides of Pontus, struck with the fact that Mercury and Venus are never seen at a great distance from

the sun, had come to the conclusion that these two planets move, not round the earth, as the sun and the other planets were supposed to do, but round the sun, so that they are sometimes nearer to us and sometimes farther off than the sun. But this idea was coldly received; it was quite ignored by Ptolemy and is only mentioned by Theon of Smyrna and Macrobius (without alluding to Herakleides), and by Martianus Capella and Chalcidius, who give the credit to Herakleides. Theon was not known in the Middle Ages, but the three other writers were held in high repute; and this led to the planetary system described by them being known to many mediaeval writers, though to most of them rather confusedly, as if they did not quite understand it. Thus Erigena says: "As to the planets which move round the sun, they show different colours according to the quality of the regions which they traverse; I speak of Jupiter, Mars, Venus, and Mercury, which incessantly circle round the sun, as Plato teaches in the *Timaeus*. When these planets are above the sun, they show us clear aspects, they look red when they are below it." Plato says nothing at all about this; but perhaps Erigena had only read Chalcidius and assumed that what he said was also to be found in the *Timaeus*. Chalcidius only mentions Venus as moving round the sun, but as he had already described the apparent motions of the two inferior planets, he probably made no distinction between them. M. Duhem seems to consider it highly creditable to Erigena that he extended the system of Herakleides to Mars and Jupiter, which nobody else did for fully seven hundred years, till Copernicus and Tycho Brahe let all the five planets move round the sun. But with regard to Jupiter, it is simply absurd to imagine that it is sometimes above the sun (i.e., more distant than the sun), sometimes below it (or nearer). As to Mars, that planet is certainly at opposition nearer to the earth than the sun is, but there is no reason to think that the astronomical knowledge of Erigena included that fact, as it is in other directions scanty enough and is confined to carelessly copied scraps from his few authorities. We need only mention his statement that half the circumference of the earth is equal to its diameter!

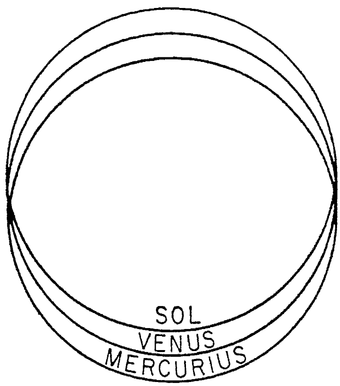
Probably also from the ninth century is another book about the Universe, *De mundi caelestis terrestrisque constitutione liber,* formerly ascribed to Bede, but quite certainly of much later date, since there are several allusions to the chronicles of Charlemagne. The author has a fair knowledge of the general celestial phenomena such as could be gathered from the above-mentioned sources, but no more. It is interesting to see that he favours the old idea sometimes met with among the Greeks, that the planets do not really travel from west to east, but from east to west, only more slowly than the sphere of the fixed stars do; so that Saturn, which comes to the meridian about eight seconds later every night, is the quickest planet, and the moon, which takes fully three-quarters of an hour longer than the fixed stars do, is the slowest—contrary to the usual idea, that Saturn, which takes 29½ years to go round the heavens in its orbit, is the slowest planet, and the moon, going round the heavens in 27 days, is the fastest.[3] We shall see presently that this primitive idea obtained many adherents towards the end of the Middle Ages. As to Mercury and Venus, the writer's opinion is, that they are sometimes above the sun and sometimes below it, as it is recorded in the *Historia Caroli* that Mercury was visible for nine days as a spot on the sun, though clouds prevented both the ingress and the egress being seen. But he does not say that they move in orbits round the sun. The writer shows himself somewhat independent of his authorities by adding a good deal of astrology and suggesting various rationalistic theories about the unavoidable "supercelestial waters."

Passing over the extremely elementary *Imago Mundi* of doubtful age and authorship, we must next mention another work formerly counted among the writings of Bede, entitled Περὶ διδάξεων *sive elementorum philosophiae libri* IV. It was written by William of Conches, a Norman of the first half of the twelfth century.[4] It is strange that it should ever have been attributed to Bede, as it

[3] See for instance Plato, *Timaeus,* pp. 38-9, Leg. 821 sq.

[4] Two manuscripts in the Bibliothèque Nationale give the author's name as William of Conches, and there are other proofs from other undoubted writings of his.

shows a freedom of thought which would have been impossible early in the eighth century. But his astronomical knowledge is often confused and erroneous. For instance, he knows that the orbit of the sun is a circle eccentric to the earth, but he imagines that the great heat in summer is caused by the sun being at that time nearer to the earth than in winter. He is aware of the difference of opinion among the ancients as to the position of the solar orbit,



whether it was just outside the lunar orbit (according to the Pythagoreans, Plato, Eudoxus, and Aristotle), or between the orbits of Venus and Mars, as taught by Archimedes and all subsequent writers, including Ptolemy. William of Conches thinks that this difference of opinion is caused by the fact that the periods of Mercury, Venus, and the sun are nearly equal, so that their circles must also be nearly equal and therefore are not contained one within the other but intersect each other. He therefore did not grasp the real meaning of the system of Herakleides, but merely conceived the three orbits to be nearly equal in size with their centres at short distances from each other and in a line with the earth; and his description agrees with a diagram given in an anonymous manuscript of the fourteenth century, copied by M. Duhem.

The question of the orbits of Mercury and Venus continued to crop up now and then, as long as Chalcidius and other late authors continued to be considered as great authorities by some writers

who were much behind their own time. The Rabbi Abraham ben Ezra of Toledo (1119-75) in several of his astrological writings, which were printed in 1507 at Venice in a Latin translation, alludes to the orbits of Mercury and Venus being between those of the moon and the sun; but in one place he says that the two planets are sometimes above and sometimes below the sun. The same expression is used in the following century by Bartholomaeus Anglicus in his encyclopaedic work *De proprietatibus rerum* (*c.* 1275). The only time that it is clearly and distinctly stated that Mercury and Venus travel round the sun is in an astrological manuscript in the Bibliothèque Nationale of the year 1270 by an anonymous astrologer to the last Latin Emperor at Constantinople, Baldwin of Courtenay. After saying that the orbits of moon, sun, and three outer planets surround the earth, he continues: "Li cercles de Vénus et de Mercure ne l'environent mie. Ainz corent environ le Soloil et ont lor centre de lor cercles el cors del Soloil; mes Mercurius a le centre de son cercle el milieu del cors del Soloil, Vénus l'a en la souraineté del cors del Soloil; et por ce sunt il dit épicercle, qu'il n'environent mie la terre, si cum j'ai dit desus des autres." The author might have lived hundreds of years earlier; he knows nothing of Ptolemy or of the Arab writers on Ptolemaic astronomy, who long before the time he wrote had become known in the west of Europe.

For while Europe had been content to pick up a few crumbs here and there, the East had been feasting on the intellectual repast left by the Greeks. Works on Philosophy and Science had been translated into Arabic, and Mohammedan authors had written textbooks founded on them and had continued the work of the Greeks in Mathematics and Astronomy. Arabic authors began to be known in the West from about the year 1000; Gerbert (Pope Sylvester II) probably wrote a book on the astrolabe founded on Arabic writings, and several tracts on the same subject were written in the eleventh and twelfth centuries in France, especially at Chartres, at that time the principal seat of learning there. Translations were also made in Italy by Plato of Tivoli; but it was in Spain, where science

was still under the protection of powerful Arabian kings, that the work of translation was chiefly carried on. The first translations were the work of a college of interpreters established at Toledo; an Arabian scholar translating a book into the mother tongue, and a Spaniard afterwards turning this into Latin. Ptolemaic astronomy became known about the middle of the twelfth century through the medium of the books of Al Battani and Al Fargani. The original work of Ptolemy, the *Syntaxis* or the *Almagest,* as it was generally called in Latin countries from a corruption of part of the Arabic title (Al-μεγίστη), was first translated about the same time by Gherardo of Cremona, who died about 1184 at the age of 73. He seems to have spent most of his life at Toledo, where he went to find the Almagest. Seeing what a great number of valuable works in Arabic were to be found there, he learned Arabic and is said to have translated no less than seventy-four different works, both by Greek and Arabian authors. But it took a very long time before people could be found capable of mastering the great work of Ptolemy.

That there were some people in the middle of the twelfth century anxious to spread knowledge of astronomy may be seen from a manuscript in the Bibliothèque Nationale, examined by M. Duhem. The name of the author of the "Tables of Marseilles" is not known; from internal evidence it appears that they were prepared about the year 1140. The author says that students of astronomy were compelled to have recourse to worthless writings going under the name of Ptolemy and therefore blindly followed; that the heavens were never examined, and that any phenomena not agreeing with such books were simply denied. He therefore decided to transform the astronomical tables of Al Zarkali, which were computed for the meridian of Toledo and adapted to Arab years, so as to arrange them for the meridian of his native city and according to years dated from the birth of our Lord. This attempt to make the Toledo tables known in Latin countries did not bear fruit immediately; but early in the thirteenth century imitations of the tables of Marseilles began to appear, adapted to the meridians of Paris, Lon-

don, Pisa, and Palermo, even for that of Constantinople, at that time ruled by Latin Emperors. The London tables date from the year 1232; the author mentions Ptolemy, but evidently only knows his work by name.[5] This is certainly also the case with the celebrated little book on the Sphere by John of Holywood (Joh. de Sacrobosco), written in the first half of the twelfth century, which continued to be a favourite text-book for three hundred years and was repeatedly printed. He only had his wisdom from Al Fargani and Al Battani, for he copies a mistake made by them and omits what they omit.

But astronomical books were far from being the only ones transmitted through the Arabs. The philosophical books of Aristotle and of his commentators, as well as neoplatonic and Arab speculations, also crossed the Pyrenees. At first they were not welcomed by the Church, and at a provincial council held at Paris in 1209 it was decreed that neither Aristotle's books on natural philosophy nor commentaries on them should be read either publicly or privately in Paris. In 1215 this prohibition was renewed in the statutes of the University of Paris. But this resistance wore off by degrees; better translations both of Aristotle and of Arab astronomers were produced by Michael Scot; while Guillaume d'Auvergne, Bishop of Paris from 1228 (died 1248), lent his powerful aid to the spreading of knowledge. He was a prolific writer, and was the first to make serious use of Greek and Arab philosophy, rejecting what was contrary to the Christian faith and combining the rest with what the Church taught, to compose a philosophical system acceptable to the Christian world. Among his writings was a treatise *De Universo,* which stands half way between the old works of Isidore, Bede, Pseudo-Bede, Honorius, and the later encyclopaedias of Albertus Magnus and Vincent of Beauvais, containing more philosophy and less theology than the former. But his opinions on celestial motions are very confused. For instance, he thinks that

[5] Similar tables, founded on those of Al Zarkali, were made at Montpellier towards the end of the thirteenth century by the Jew Jacob ben Makir, generally called Profatius.

one can "by means of astronomical instruments and certain geometrical instruments" determine the distance of the earth from each of the fixed stars and from each of the planets. The waters above the moving spheres are neither fluid nor in a state of vapour; they form an ethereal mass, perfectly transparent and immobile, separating those spheres from the Empyrean.

The introduction of Aristotelian natural philosophy in the Universities of Paris and Oxford brought about a prolonged strife between Aristotelian ideas of the construction of the Universe and the Ptolemaic system of the world; or rather a revival in France and England of an old dispute which had existed first in the Hellenistic and then in the Mohammedan world. Aristotle had adopted the "homocentric spheres" of Eudoxus to account for the motions of the planets; but though this would to some extent explain the chief irregularities in these motions, continued observations soon showed that the system was insufficient to "save the phenomena," particularly as it could not account for the variable distance of a planet from the earth. A totally different system had therefore been developed at Alexandria in the course of nearly four hundred years, until it was completed by Ptolemy. According to this, a planet moved on the circumference of a circle (the epicycle), the centre of which travelled on a larger circle (the eccentric or deferent) the centre of which was at some distance from the earth; but in such a manner that its motion was uniform, not with regard to the centre of the deferent, but as seen from another point, the *punctum aequans*. The centre of the deferent was midway between that point and the earth. Further complications had to be introduced to account for the motion in latitude of the planets. From a mathematical point of view this system was perfect, as it really could "save the phenomena," that is, represent the actually observed motions with an accuracy nearly corresponding to that attainable by the crude instruments then in use. But it was totally at variance with Aristotelian Physics, the adherents of which viewed the movements around points outside the centre of the world with extreme disfavour. Long before Ptolemy's time attempts had therefore been

made to reconcile the two systems. This was simple enough, as long as the deferent was assumed concentric with the earth. The epicycle might then be conceived to be the equator of a solid sphere, rolling between two solid concentric spheres. This idea is described by Theon of Smyrna (soon after A.D. 100), but it must be much older. It became untenable, as soon as the deferents became excentric circles. In the *Syntaxis* Ptolemy merely alludes to planetary spheres when describing the order of the various orbits (ix. 1); and his attitude with regard to the equivalence of the epicyclic and eccentric theories shows that he had broken with the idea described by Theon and did not attribute any reality to the multiple motions of the *Syntaxis,* but merely considered them as geometrical means of representing the real motions. But in a later work, *Hypotheses of the Planets,* or rather in the second book of it, Ptolemy's ideas are quite different.[6] Here he proposes to do for the complicated theories of the *Syntaxis* what the system of Theon did for the simple epicyclic motion, producing not a mere model but a real representation of the constitution of the universe, as real as that described in Aristotle's *Metaphysics.* The epicycle-sphere now fits between two eccentric spherical surfaces which touch two other surfaces (an inner and an outer one), in the common centre of which the earth is situated. This system of the world does not seem to have been a success; in the neoplatonic schools the theories of the *Syntaxis* appear to have been more valued, although the old Platonic and Aristotelian dogma, that every celestial motion must be circular and uniform round the centre of the earth, still found partisans.

Towards the end of the eighth century Mohammedan nations began to become acquainted with Alexandrian astronomy, in the first instance through the medium of northern India, where a knowledge of Greek science had spread in the first couple of centuries after the conquests of Alexander the Great.[7] The system of spheres

[6] The Greek original is lost, but a translation into Arabic has been preserved, from which a German translation was printed in 1907 (*Claudii Ptolemaei Opera,* ed. Heiberg, T. ii).

[7] From what M. Duhem says (vol. ii, p. 213) it looks as if he thought that Arabian astronomy was founded on indigenous Indian knowledge. But it is

seems to have appealed strongly to Eastern minds; and throughout the time when astronomy continued to be successfully cultivated in the Mohammedan world we find that various combinations of spheres were proposed by people who could not be satisfied with the Ptolemaic system of circles, while the latter was accepted and used by professional astronomers. The first to describe the spheres was Tâbit ben Korrah, in the second half of the ninth century. He seems to have been the first to fix the number of spheres at nine, and he was followed by the "Brethren of Purity" in the tenth century and by Ibn al Haitham (*c.* A.D. 1000).[8] The necessity of introducing a ninth sphere above the eighth sphere (the sphere of the fixed stars) was due to the imaginary phenomenon of trepidation or oscillatory movement of the equinoxes. This dates back to the time before Ptolemy, but he quite ignored it and taught that the Precession of the Equinoxes is uniformly progressive, while Tâbit (though speaking with a certain reservation) accepted the phenomenon of trepidation as real. The Arabian combinations of spheres were mainly borrowed from Ptolemy, though with modifications. It was particularly in Spain that the opposition to the Ptolemaic system of eccentrics and epicycles came to the front, being intimately connected with the rapid rise of Aristotelian philosophy in that country in the twelfth century, which culminated in the work of Averroes, the greatest philosopher of Islam. An ingenious attempt at reviving the principle of homocentric spheres in a perfectly novel manner was made by the astronomer Al Bitrugi (Alpetragius), though the leading idea was probably due to the philosopher Ibn Tofeil.

This system of homocentric spheres differs from that of Eudoxus and Aristotle by assuming that the prime mover (the ninth sphere) everywhere produces only a motion from east to west, the independent motion of the planets from west to east being rejected. We

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quite certain that the Indians derived all their knowledge of planetary motion from the Greeks. See J. Burgess, in *Journal of the R. Asiatic Society,* October 1893, pp. 746 sq., and Dreyer, *Hist. of the Planetary Systems* (Cambridge, 1906), pp. 240 sqq.

[8] Known in the West as Alhazen, author of a celebrated book on Optics.

have already mentioned that this was a very old idea which had been revived in Europe by Pseudo-Bede. But Al Betrugi saw that this was not sufficient, as not only is the pole of the ecliptic different from that of the equator, but the planets do not even keep at the same distance from the pole of the ecliptic but have each their motion in latitude as well as a variable velocity in longitude, all of which had to be accounted for. This was done by letting the pole of each planet's orbit describe a small circle round a mean position (the pole of the ecliptic) in the synodic period of the planet.[9] But the system was not worked out in detail; and only philosophers who wanted nothing more than a representation of the principal phenomena could be satisfied with it. In the eyes of astronomers it had many faults, the greatest being (as in the case of the system of Eudoxus) that it assumed a planet to be always at the same distance from the earth.

When Michael Scot about the year 1230 had produced his translations, the attacks of Averroes and Al Betrugi on the epicyclic system spread rapidly among the Scholastics. Though people who only desired to account for the apparent motions of the planets as seen projected on the celestial vault continued to follow the rules of Ptolemy, philosophers were greatly concerned about the contradiction between Aristotle and Ptolemy. During the whole of the second half of the thirteenth century this agitated the two rival orders of Dominicans and Franciscans, who dominated the University of Paris. Among the former Albertus Magnus was at first the most prominent. He was much attracted by the system of Al Bitrugi, which he thought was very simple, because he ignored the small circles and thereby made it quite useless. It was in this simplified form only that the system continued to be known to most of the Scholastics, which sufficiently characterizes their superficial knowledge of celestial motions. Yet Albert was quite aware of the fatal

[9] The account given by M. Duhem of this historically important system is most unsatisfactory. For further details see *Hist. of the Planetary Systems,* p. 265, a book which seems to be unknown to M. Duhem. It is curious to see how astronomical historians have fought shy of explaining the system; see e.g., Delambre, *Hist. de l'Astr. du Moyen Age,* p. 174.

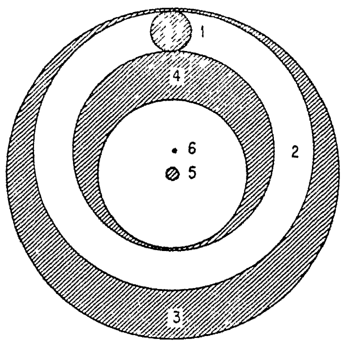
objection to every form of homocentric system, and he finally declared for Ptolemy. The same was the case with his disciple Thomas Aquinas. For the simplified system of Al Bitrugi he substituted the idea that celestial bodies are animated by two movements; the first is a uniform rotation from east to west, a principle of eternal duration; the second is a rotation from west to east round the poles of the ecliptic, a principle of generation and transformation, a movement in which the different orbs take part to a lesser extent the more noble they are. Like Albert he ends by abandoning Averroes for Ptolemy, chiefly on account of the change of distance.

If we turn to the Franciscans we are met with more hesitation as to the choice between the rival theories. Bonaventura, the Doctor seraphicus, does not seem to have devoted much attention to astronomy. According to him there is a ninth heaven, the aqueous one, which is the primum mobile; some philosophers have perceived that the firmament has a proper motion of 1° in a hundred years,[10] but whether this is true or not it is certain that Doctors of Theology admit that there is a moving heaven without stars.

But in Roger Bacon we meet at last with a man who was thoroughly acquainted with the astronomical writings both of Greeks and Arabs. At Oxford he was under the influence of Robert Grosse-Teste, afterwards Bishop of Lincoln, who had devoted some attention to astronomy and was a follower of Ptolemy, except when he wanted to be a metaphysician and had to follow Al Bitrugi. But it was not till Bacon went to Paris (about 1235) that he was able to study scientific problems seriously. M. Duhem gives a lengthy account of a manuscript in the municipal library of Amiens, containing several series of questions on the *Physics* and *Metaphysics* of Aristotle. They are probably written by pupils of Bacon at Paris, at latest about the year 1250. The questions on the *Metaphysics* must be the earliest; the teacher does not appear to know Ptolemy's works, and only to have heard of Al Bitrugi. The questions on Aristotle's *Physics* show more knowledge, especially

[10] The amount of precession according to Ptolemy.

of the system of Eudoxus and of Precession. The subsequent writings of Bacon show how he persevered in his study of cosmology and astronomy; but he continues all his life to hesitate between the two systems of the world. He studies the *Almagest,* he borrows from Al Fargani what he says about the dimensions of the planets and of their orbits; on the other hand he makes himself thoroughly acquainted with the theory of Al Bitrugi, the details of which hitherto had scared readers in France. In his *Opus tertium* he gives



a carefully written summary of that theory, and then gives an account of the system of solid orbs described by Ptolemy in his *Hypotheses* and taken up by Ibn al Haitham. Bacon acknowledges that it does away with many of the objections formulated by Averroes against the epicyclic system, but he thinks that there are too many questionable hypotheses in it. His main objection is, that the two bodies between which each deferent is comprised have in their various parts different thickness,[11] but this cannot be the case in celestial bodies on account of their simple and homogeneous nature. He also thinks that a celestial body cannot be supposed to be devoid of all motion. Other objections made by Bacon seem to show that he cannot have been acquainted with the second book of Ptolemy's *Hypotheses,* the Greek original of which was probably lost before that time; and that he only had before him an incomplete résumé of

[11] Compare the diagram in the *History of the Planetary Systems,* p. 259 (reproduced above), the surrounding sphere and its complement.

the systems of spheres of Ptolemy and Ibn al Haitham.[12] Bacon therefore never reached any conclusion as to which system of the world was the true one.

But a younger contemporary of Bacon among the Franciscans, Bernard of Verdun, made up his mind to break with Aristotle and Al Bitrugi. In a *Tractatus optimus super totam Astrologiam,* of which two manuscripts are known to exist, and which shows familiarity with Bacon's works, he begins by counting up the facts which must be explained: the change of velocity of the planets; the variability of the moon's diameter, the moon being more or less completely eclipsed even in the same point of the ecliptic; the upper planets (particularly Mars) being brightest at opposition to the sun, while Mercury and Venus are of greater brightness after leaving the sun and moving eastward than when they leave it to move westward. All these facts distinctly contradict all homocentric theories, and Bernard therefore finally rejects the system of Al Bitrugi, with which he shows that he is well acquainted. In the system of spheres of Ptolemy or its imitation by Ibn al Haitham he sees the means of shielding the Ptolemaic system from Aristotelian attacks; and as the theory of eccentric and epicycles is the only one which is able to produce tables of planetary motions and "save the phenomena," Bernard does not hesitate to proclaim it as the true system. The above-mentioned objection raised by Bacon he brushes aside by saying that the surrounding spheres, &c., are not proper celestial bodies, but like those parts of a cithern which do not give any sound.

This treatise by Bernard of Verdun seems, at least for the University of Paris, to mark the epoch when the Ptolemaic system began to reign absolutely among students of astronomy; the adherents of Al Betrugi had to give up the struggle. There are various other tracts in existence from the time around the year 1300 which confirm this result, while they show at the same time that the question about the precession of the equinoxes, whether it was a steady

[12] The fact that he calls the system *Ymaginatio modernorum* also points to his only having known an Arabic account of it.

progressive motion or only an oscillation, was still unsettled, which involved uncertainty as to the number of spheres above those of the planets. The Alfonsine Tables, prepared under the direction of King Alfonso X of Castille, were finished about 1270, but they were probably not at once issued to the public. At any rate it is certain that they were not known at Paris until towards the end of the thirteenth century, the tables of Al Zarkali (the tables of Toledo) being still in use there. The time had come however when some people among the Christian nations had begun in a small way to occupy themselves with practical astronomy, instead of merely speculating whether there were nine or ten heavens, or considering whether an astronomer or a philosopher was the best guide among the stars. There is a codex in the Bibliothèque Nationale which contains several tracts from the end of the thirteenth and the beginning of the fourteenth century bearing witness to this change of study. Among these are two by Guillaume de St. Cloud, one being an Almanac for twenty years from 1292, the other a Calendar, the date of which is 1296, which gives the time of entry of the sun into each of the twelve signs for two hundred years before and after the year 1296. At the beginning of the Almanac it is stated that the tables of Ptolemy of Alexandria, Tolosa (?), and Toledo do not agree with observations; there is no mention of the Alfonsine Tables. From observed solstitial altitudes of the sun in 1290 the obliquity of the ecliptic is found to be 23° 34′ and the latitude of Paris 48° 50′. Guillaume also determines the time of the spring equinox of 1290 (March 12, 16^h) and corrects the errors of the Tables of Tolosa by the simple expedient of correcting the mean motions thus: of Saturn by — 1° 15′, of Jupiter by + 1°, of Mars by — 3°.[13] M. Duhem does not explain what the Tables of Tolosa are, but a fragment of a tract by Guillaume de St. Cloud quoted by Nicolaus de Cusa gives the clue to this riddle.[14] The fragment gives the errors of the Alfonsine Tables for the three planets, and the amounts are exactly the same as those given in the codex as the

[13] Duhem, T. iv, p. 18.
[14] Ibid., p. 23.

errors of the Tables of Tolosa. This shows that the Alfonsine Tables had become known at Paris by the year 1292.

The same interesting codex also contains a tract by Johannes de Muris, a native of Normandy. He quotes the determination of the equinox of 1290 and describes how he repeated it at Evreux in 1318 (March 12, $16^h 40^m$); he says this agrees with King Alfonso's and Guillaume de St. Cloud's observations. Joh. de Muris and Firmin de Belleval wrote a report on the reform of the calendar, by order of the Pope, which if adopted would have settled this question more than two hundred years before the time when the Gregorian reform was actually carried out. Firmin wrote a little book on Meteorology which was printed at Venice in 1485.[15]

Another astronomer of the first half of the fourteenth century who must not be passed over here, though not connected with Paris, was a Jew, Levi ben Gerson of Avignon, who died in 1344. He wrote against the system of Al Betrugi and (what is more important) he invented (or at least introduced) the instrument known as Baculus Jacobi or Cross Staff for measuring the angular distance between two stars; and better still, he applied a diagonal scale to it. The latter invention (not mentioned by M. Duhem) appears to have remained unnoticed for about two hundred years.[16] Practical astronomy was also cultivated by Johannes de Lineriis (Jean de Linières), from whose hand there are several manuscript treatises

[15] *Opusculum repertorii pronosticon in mutationes aeris.* M. Duhem (T. iv, p. 42) says that according to a manuscript copy in the Bibl. Nat. there was an interval of 68 years between the Alfonsine Tables and the epoch of certain tables; this gives the date of the book $1252 + 68 = 1320$. The sentence quoted occurs in the printed book on f. 12v at the foot, but the interval is 86, which gives 1338. The context shows that 86 is a misprint; yet compare f. 3v, where 1338 is given as the epoch of some star-places brought up from Ptolemy's catalogue.

[16] M. Duhem (T. iv, p. 40) says that the use of the baculus was introduced among Portuguese navigators by the German scientist Martin Behaim towards the end of the fifteenth century. But is has been conclusively shown by Joaquim Bensaude (*L'Astronomie nautique au Portugal à l'époque des grandes découvertes,* Berne, 1912) that the baculus was known in Portugal long before the time of Behaim, to whom and his compatriots the Portuguese owed nothing. M. Duhem quotes this book in a footnote without noticing that it demolishes what he has just stated in the text.

in the Bibliothèque Nationale, among them a guide to the use of the Alfonsine Tables and *Theorica Planetarum,* anno Christi 1335. The latter is an account of the Ptolemaic System from the *Almagest* (without spheres); there is a chapter on the motion of the eighth and ninth spheres, in which it is shown that Tâbit's theory of oscillation must be rejected, as the equinox has now receded more than that theory allows; the author is inclined to adopt the theory proposed by Alfonso X combining progressive and oscillatory motion. Jean de Linières also produced a catalogue of positions of forty-seven stars, the first attempt in Europe to correct some of the star-places given in Ptolemy's Catalogue.[17]

Other manuscripts from the fourteenth century show that various teachers at Paris continued to expound the Ptolemaic system, with or without spheres. At the beginning of the century Aegidius, a native of Rome, wrote a Hexaëmeron (printed several times in the sixteenth century) in which he proposes to let the epicycle-sphere lie, not between two spheres, but in a cavity in the celestial matter of the form of an anchor ring. Some of these writers had not a very clear idea of what they wrote about; e.g., Albert of Saxony in a Commentary to Aristotle's *De Caelo* (also printed several times) says that the moon does not move in an epicycle; for if it did, the figure of a man in the moon carrying a bundle of sticks would sometimes be seen upside down! He means of course that the moon would not always turn the same side to the earth.

Though M. Duhem several times alludes to the Alfonsine Tables, he has evidently not examined any codices of them. He has thus missed the interesting fact, that the tables first published at Toledo about the year 1270 were totally different from those first printed in 1483. The latter were a modification of the original tables made at Paris, probably by Jean de Linières. At Oxford, where there seems to have been a good deal of interest taken in astronomy from

[17] See a paper by G. Bigourdan in the *Comptes rendus,* December 1915 and January 1916. The catalogue was printed in Riccioli's *Astronomia Reformata,* i, p. 216.

the beginning of the fourteenth century, the tables in their original form remained in use longer than anywhere else.[18]

While science had thus begun to be earnestly cultivated in France and England, Italy had remained behind. Though Gherardo of Cremona had translated the *Almagest* about the year 1175, more than a century passed before a single Italian studied it, while the text-book of Al Fargani was the usual guide. But it is remarkable how badly even that book was understood, the most extraordinary blunders being made by the best of the Italian writers. Dante is an honourable exception; there are no blunders in his cosmological ideas, neither in the *Divine Comedy* nor in the *Convivio*. The latter shows the craze for astrology which prevailed in Italy, while this branch of learning was at Paris always of secondary importance. The Italians took no part in the dispute whether a system of Physics deduced from peripatetic principles or a science constructed to agree with observed facts should conquer. Only Petrus de Abano (about 1300) alludes to it, but the dispute had been settled before he went to Paris. In the Universities of Spain and Portugal the fight did not begin till the middle of the fifteenth century and lasted about a hundred years, during which time objections were raised which had been demolished elsewhere long before.[19]

The second half of M. Duhem's fourth volume and the whole of the fifth deal with Arabian and Scholastic Philosophy. His account of mediaeval cosmology and astronomy reaches to the end of the fourteenth century, except that it does not deal with any English writers after Roger Bacon. The revival of astronomy in Europe has hitherto been supposed to date from the middle of the fifteenth century, and to have commenced with the labours of Cusa, Peur-

[18] Cf. Dreyer, "On the original form of the Alfonsine Tables," in *Monthly Notices of the Royal Astronomical Society*, vol. lxxx, pp. 243-62.

[19] In the south of France a last attempt to substitute spheres for epicycles and eccentrics was in the fourteenth century made by Levi ben Gerson in his work *Milchamot Adonaï*, of which an account was published by Carlebach in 1910 (Duhem, v, pp. 201 sqq.).

bach, and Regiomontanus in Germany. We know now from the researches of M. Duhem that the revival began in France fully a hundred years earlier, while the studies of M. Bensaude have shown that the scientific light spread by the Arabs in Spain and Portugal had never been put out, so that the navigators who found the way to the Indies and to the New World had nothing to learn from German astronomers. We shall look forward with great interest to the promised sixth volume of M. Duhem, while deeply regretting that his early death should have prevented him from completing this vast monument of learning and perseverance.

R. J. Forbes

METALLURGY AND TECHNOLOGY IN THE MIDDLE AGES*

The epithet "barbarian," attached to the Middle Ages by the Renaissance, has stuck tenaciously. Even though the historians of science and technology should know better by now, many of them still have at the back of their minds, the idea of the "Dark Ages" in which science and technology were stagnant. This view is obvious in many books on the history of technology.

It is true that in the Middle Ages science was more or less the handmaid of religion and that natural philosophy in those days was less concerned with experiment and observation than with philosophical argument. The bonds with technology and its practical experience were virtually severed. Hence we should not look for evidence on technological evolution in medieval scientific documents. The evidence is buried in local documents which are rarely studied by the historian of science. Legal, economic and social historians have investigated these documents, manuscripts and letters, each from his own angle, but little technical information has been published nor have illustrations, paintings and drawings been collected.

* Reprinted from *Centaurus,* III, 1-2 (1953), pp. 49-57, with the permission of *Centaurus* and of the author.

Therefore our evidence on medieval technology is still scrappy. On the other hand we have by now realised that the fall of the Roman Empire nowhere meant a gap in technical evolution. It is also clear that from the early Middle Ages onwards important discoveries and inventions were added to our material civilisation. Not only was there a constant trade with the Mediterranean and a continuous development of the technological achievements of the ancients. The "barbarian" invaders themselves brought widely diverse gifts to Western Europe such as the use of furs and trousers, a new type of house better suited to the climate than the old patio house, felt-making, cloisonné jewelry, skis, the domestic use of soap and butter, production of barrels and tubs, falconry and new economic plants such as oats, rye, spelt and hops. It is not yet fully known which of these elements are indigenous and which may have been derived from Arab civilisation or even further East by the way of the steppes.

Last but not least new spiritual forces were at work which changed the development of science and technology profoundly. The western world was a Christian world. It held that man was created in God's image and that all souls were equal to God. Man should never be degraded to become a machine. As the centuries flowed by this moral tenet became a strong force destroying and counteracting the use of human slaves as a source of energy. It stimulated the creation of machinery to help mankind and to bring man greater comfort. God had placed nature at man's disposal. Men did not only begin to dream of machinery to take over their heavy duties; they built them—and even strove to make fully automatic machinery, of which the ancients had never even dreamt.

This rise of mechanical power sources was of the utmost importance for the mass-production of metals. A three-fold development was involved. First of all there was the improved harnessing of horses introduced in the ninth century, which allowed the horse to pull loads efficiently and turned it into an economic source of traction.

Secondly the wind-mill came to the West, but as it found its way

mainly to the low-lying windy plains along the Atlantic, it hardly plays a part in the development of metallurgy.

The third development, however, that of the water-wheel, was a turning point in the production of metals. It had been introduced from Pontus into the Mediterranean world in the first century B.C. and classical authors like Vitruvius and Pliny refer to the "hydraletes." It is well-known that water-wheels were used in Antiquity. The mills built by Trajan on the Janiculus played a part in the flour-production of Rome during the fourth to seventh centuries. We know of floating water-wheels on the river Tiber. A water driven saw-mill is mentioned in the third century and others were used for fulling and pressing olives.

Yet this form of mechanical power was never popular in Antiquity. The rivers of the Mediterranean world flowed too irregularly to provide a constant supply of water to the wheels. But above all there was no social urge to replace the fairly abundant human power by machinery, no trend to economise on human energy. Vespasian refused to allow the use of a water-driven hoist "lest the poor have no work." When Constantine the Great adds the flour-mills to the places of penal servitude this means that the majority of flour-mills were still hand-driven.

Already in the second century A.D. we find water-driven flour-mills working for the Roman army at Tournus (Bourgogne) and at Barbegal near Arles a double set of eight water-wheels built cascade-wise ground flour rather inefficiently. Their use spread rapidly in Gaul. In the fourth century two mills are mentioned at Dyon and Geneva, in the sixth we hear of six, but many more references date from Frankish times. By the eighth century water-wheels are well established in Central Europe (Thuringia, Odenwald, Mühlhausen).

Cassiodor explains that the sites of monasteries were often chosen to provide ample water power. The first water-wheel in England is mentioned in a document of 838 A.D.; in the tenth century they have penetrated to Ireland. Water-wheels are quite common in the *Capitulare de villis* and the Domesday Book. By the twelfth

century they have spread to Scandinavia and the Baltic and around 1200 they appear in Iceland.

However, the water-wheel was not to remain merely a mechanical means of grinding corn. It soon became the principal source of mechanical power of the Western World and, with the windmill, held its own until well into the Industrial Revolution. Both undershot and (the slightly later) overshot wheels were used by the Egyptians for the supply of water to the fields as Strabo reports. In Western Europe the Cistercian monks used mostly wind-mills for the drainage of fens and lakes.

In the higher regions water-wheels became a very important factor in mining and metallurgy. They were used to drive hoists. By the twelfth century they were introduced in the copper mines of the Harz mountains and the silver mines of Trient. Water-driven hammers for crushing ores are mentioned in Styria around 1175. Water-driven forge-hammers were common in the thirteenth century. In the first half of the fourteenth century water-power was used in wire-drawing. Grindstones were water-driven in the Wupper valley since the thirteenth century.

This general application of the undershot water-wheel in the Middle Ages enabled the medieval metallurgists to make larger and heavier metal objects. From the twelfth century onwards water-driven bellows supplied a much larger quantity of air to the larger furnaces then built. We shall revert to this when discussing the new cast-iron metallurgy.

The manifold application of the water-wheel and its gearing to other machinery led to much practical experience and theoretical interest in cams, gears and other aspects of mechanics. This is quite obvious when the first printed books begin to show the achievements of Leonardo da Vinci's contemporaries, who must have based their machinery on the experience of earlier generations. It includes the common use of the crank, one of those inventions that seem to go back to the early Middle Ages.

Again we should not be surprised if further research reveals a

connection between this gradually increasing practical experience with cams, gears and machinery and the theoretical considerations by Nicolas Oresme and his generation. The rise of machinery cannot have failed to influence the rising science of mechanics. Both Grosseteste and Roger Bacon express interest in machinery.

The water-wheel, therefore, forms the first and principal factor in the development of medieval metallurgy by providing more powerful sources of blast-air and mechanical means of working and shaping larger pieces of metal. The other facts in metallurgy—mining ores, producing fuel, and metallurgical furnaces—must now be discussed.

We know far too little about medieval mining methods. Most of our evidence has been culled from the writings of legal historians and local antiquaries, who very often approach their documentary evidence from an angle differing widely from that of the historian of technology. But we are sure that Roman traditions were never lost. New departures were attempted which received a severe set-back at the time of the Black Death and again after the discovery of the New World when many European silver and lead mines were closed forever. This is quite clear from the Bergbüchlein of the sixteenth century and more especially from Agricola, whose references to ancient classical practice are very frequent. The Harz, Saxony and Bohemia were, however, the best mining schools of Europe long before Agricola's days.

Mining was still limited to shallow shafts which could not reach beyond the subsoil water. The advent of proper machinery, pumps for draining the mines and mechanical fans for proper ventilation, would open up a new area. But even the simple forms of hoists, chain-and-bucket pumps and other machinery driven by man- or horse-power cost money. Mines, no longer state enterprises, were worked by miners grouped in voluntary associations. As the machinery became more costly and larger undertakings were demanded they were financed by the bankers of early capitalism. The Fuggers, the Welsers, the Thurzos and their French and Italian

colleagues were deeply involved in the mining and production of metals.

We have very little information on the rare attempts to use coal for the production of metals from their ores. Coal was mined in the Liège district before 1198. In Newcastle the coal-miners obtained confirmation of earlier privileges in 1234. In Germany the Saar coal mines were producing in the fourteenth century which also saw an extension of this production in the Liège district, Scotland and England. The "sea-coal" trade with its special "keels," flat bottomed boats of shallow draught, became fairly important, but this coal seems to have been used for domestic consumption only.

The metallurgical fuel par excellence was charcoal which was still produced in the old classical way. Grave difficulties loomed ahead when the demand for metals rose considerably. This was due to the rise of the cities in the twelfth and thirteenth centuries and their growing engineering problems, such as the building of churches, housing, harbours, moles, canals and other public works and the rise of modern warfare involving fire-arms and guns. The shortage of timber made itself felt in many districts and led to restriction and even to the cessation of metallurgy in certain regions. Thus in England the shortage of timber meant the end of metallurgy in the Weald. The pressing need for other fuel eventually led to attempts to use coal for metallurgy, but these fall in a later period. The final solution was reached through the experiments of the Darbys in the eighteenth century. Thus medieval metallurgy remained a powerful factor in the deforestation of certain regions of Europe.

European metallurgy was now centred in the production of iron. Already in classical times the Iberians and Gauls were proficient iron smiths and the production of bronze weapons and tools declined from the second century B.C. onwards. The Celtic smiths of Gaul produced their famous swords by welding steel strips onto strips of wrought iron, but these swords bent easily in use and had to be straightened out. Here again, classical tradition was never

lost. The strong guilds of smiths of the Roman Empire survived the storms and their position was strengthened by local statutes. Further specialisation is shown in the rise of the farriers, white-wrights, gunsmiths, pewterers and other guilds.

A great variety of processes and furnaces were used. The primitive bloomeries, producing blooms of 60-70 kgrs., survived up to the nineteenth century. Corsican and Catalan forges were used and made more efficient in certain districts by the introduction of blast air under pressure produced by falling water, a practice that seems to have arisen in medieval Italy. Osemund furnaces, forerunners of the true blast furnaces, produced about 5-6 charges of 15-20 kgrs. of wrought iron a day. Steel was manufactured by widely different processes. In Styria iron ores containing manganese compounds were reduced at high temperatures, absorbing carbon. Other districts such as Norway and Brescia (Italy) used case hardening processes or even decarbonised in small quantities.

The most famous centres were Styria, Carinthia (producing the *"lymbriquestuff"* and *"iebrookstuff"* of the English market), Tyrol, Amberg, the Harz, Norway, Siegen, Liège (also famous for its brass or "dinanderie"), Spain, Normandy, the Weald, the Mendips, the Forest of Dean and Rockingham forest.

The most important progress in medieval metallurgy was the commercial production of cast-iron. Potentially this manufacture was possible in the furnaces then known, given the proper processing time and temperature of the charge. In classical times cast-iron had been produced accidentally but mostly rejected because the technique of its processing was still unknown. As the furnaces increased in size, due to the trend of producing larger charges more efficiently, the frequency with which cast-iron was obtained accidentally increased. However, the temperatures common in early medieval furnaces were not sufficient for commercial production of cast-iron. In general the blast air was still supplied by bellows which were at best powered by man- or horse-driven treadles. The turning point was the coming of water-driven bellows. Only then were

the size of the furnace (that is, processing time) and the amount of blast air (that is, temperature in the furnace) both sufficient for commercial production of cast-iron.

This production of cast-iron was still primitive and was perfected haltingly and gropingly. The true *"Gusz aus dem Erz"*—that is direct production from the ore in a real blast furnace—seems to date from the early fifteenth century. The fining of this crude cast-iron in order to reduce the carbon content of the rough brittle product to the desired amount is an accomplishment of the sixteenth century. But the first primitive blast-furnaces go back to the early fourteenth century. They are reported in the Liège region in 1340 and quickly spread to the Lower Rhine and to Sussex, and in 1360 they appear in Sweden. In the same century we hear of the first cast-iron specialist, Merckeln Gast of Frankfort, who casts guns.

The production of cast-iron was stimulated by several trends and inventions. First of all there was the rise of military engineering. The invention of gunpowder goes back to the late thirteenth century. Attempts to make fire-arms seem to have been undertaken on the Lower Rhine about 1325. This technique soon spread to Italy and France. The first attempts used wrought iron, for instance, in the form of strips held together by bands of iron. These early guns fired bronze or stone cannon-balls. Though breechloading was attempted at an early date, the technique of producing gas tight breech blocks was still impossible because metal surfaces could not yet be finished with the required precision. Hence muzzle-loading was the common system.

Soon these firearms were produced in cast bronze. This was a technique that had grown up with the use of bells in church towers. From the fifth century onwards it had been perfected and many generations since Theophilus had added small improvements. The hammering and drilling of proper guns were no mysteries for the bronze-smiths of those days. They gradually adapted their technique to the new requirements of the fire-arm proper. Even a primitive form of "rifling" was known.

The new material, cast-iron, seemed very suitable for these applications. From 1325 onwards it was more widely used, gradually displacing bronze. The stone cannon-balls disappeared gradually and were replaced by cast-iron ones. This use of metals for fire-arms introduced a potent new factor into technology. It soon became clear that the technique of producing individual guns with their own series of cannon-balls or bullets was most inefficient. Hence standardisation of fire-arms was taken in up in many places, culminating in the standard ordnance propagated by the famous artillery schools of Venice and Burgos in the early sixteenth century. This tendency to standardise parts of machines and tools spread to the dockyards and navies. It proved a powerful stimulant towards the manufacture of precision tools, parts of machinery and the machinery for their production.

Standardisation of parts led to a closer study of finishing processes in metallurgy. The great experience of medieval smiths in welding, chasing and embossing, hammering and grinding were put to use in many fields. Needles, nails, forks, scissors, shears, thimbles and files were already produced by specialists and standardisation set in quite early. Wire-drawing seems to have been invented in the eleventh century. The production of the steel for wire-drawing was now undertaken in various centres and the application of water-power to this branch of metallurgy dates from the early fourteenth century.

Metallurgy in general applied man- or animal-driven treadles (the English "olivers") more liberally and with the advent of water-power mass-production of metallurgical objects was ensured. The new material, cast-iron, soon served to produce mortars and cannons and their ammunition, anvils, cooking utensils, and irons, fire-backs and graveslabs. Sheet metal was already produced and rods manufactured from these sheets by shearing and slitting. This higher metallurgical skill is probably one of the factors contributing to the rise of mechanical clocks in the later thirteenth century. Here well-designed parts, such as the foliot balance (a simple form of escapement of the early fourteenth century) and gearing, made

possible the requisite degree of precision and hence the utility of these mechanical weight-driven clocks. Thus metallurgy contributed to one of the instruments which was to help to build the science of the seventeenth century.

The great importance of military engineering for metallurgy is clear from the "*Feuerwerks-* and *Kriegs-bücher*" (such as the illustrated manuscript of Konrad Kyesser, 1395) a series which culminates in the books produced by Biringuccio and Agricola. Its main influence, apart from the factor of standardisation, is to be seen in a series of small inventions. This is logical as the basic metallurgical processes, both physical and chemical, could not yet guide the metallurgist. The gradual development of metallurgy and pyrotechnics stimulated scientific interest in the basic processes. It was definitely helped by the art of assaying which formed the basic control of practical metallurgy.

It is often insufficiently recognised that this art of assaying was real quantitative analytical chemistry, with tools and balances enabling the metallurgist to obtain a fair precision in the analysis of his ores and products. Though here again the basic chemistry of the different tests was not yet understood it did create a sense of quantitative relations between certain chemical compounds which established a body of knowledge for later generations. These assaying results form the most tangible chemical results of the practical metallurgists and the more theoretical alchemists of the Middle Ages. Assaying is also partly responsible for the use and production of mineral acids in the Middle Ages.

Newton, when writing his *Principia* to establish the laws of the macrocosmos many generations later, was also interested in finding similar laws for the microcosmos. Therefore he turned to the notebooks of the alchemists and, as we are told by his assistant Humphrey Newton, "when he kept his furnaces smoking during all summer he repeated the tests and experiments with antimony and an old mouldy book called Agricola de Metallis lay on his table." It was a fitting tribute to the ancient metallurgists that a

truly scientific mind like Newton should first turn to assaying experiments to test the laws of the structure of matter.

The great demand for bronze and iron, the scarcity of fuel and the gradually increasing difficulty of draining the mines combined to make tin an ever scarcer metal until the new resources in the New World and the Far East were tapped. As tin and pewter had been the most common materials for household vessels, this made it necessary to find a cheaper material for these purposes. Here metallurgy stimulated the rise of the glass industry, which from the fourteenth century onwards began to produce glass vessels for common use. At the same time the more general use of pottery stimulated this art to adopt new tin and other glazes and new forms more suitable for common use. Here again progress was slow but constant as the potters and glaziers groped towards better techniques experimentally.

Metallurgy, therefore, stimulated by many factors and producing new metals, amongst which cast-iron was foremost, gathered a body of technical, mechanical and chemical (assaying) knowledge for future generations. It stimulated and was affected by standardisation of its products, better finishing techniques and new fields of application such as military engineering. The application of water-power made most of these things possible, it was itself the outcome of a long standing desire for mechanisation and, apart from experimentally building up engineering technique, it also led (along with ballistics), to the theoretical study of mechanics and mathematics.

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